CONTROLLERS
for
ELECTRIC MOTORS

An electric controller is a device, or group of devices, which serves to govern, in some predetermined manner, the electric power delivered to the apparatus to which it is connected.

(American Standards definition #25.05.005)

CONTROLLERS
for
ELECTRIC MOTORS

A Treatise on the Modern Industrial Controller with Typical Applications to the Industries

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CONTROLLERS FOR ELECTRIC MOTORS

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PREFACE

The object of this book is to bring together in one volume sufficient material on controllers to give technical students, operating engineers, and purchasers and users of electrical apparatus a good general idea of their design and operation.

The types and methods of control described are illustrative of those in general use. No attempt has been made to represent all types of commercial equipment. Special control systems, such as those applied to elevators, steel mills, and paper mills, have not been included, since a detailed knowledge of the performance problem is necessary for an understanding of them. The information given here can always be supplemented by exact data covering the particular design under consideration.

Some elementary chapters have been included for the benefit of readers who have had little experience with control apparatus. Most of the diagrams are of an elementary nature. When it is necessary to repair or adjust a controller, a diagram and instructions should be obtained from its maker.

The senior author's previous book, which was published by the D. Van Nostrand Company, is now out of print. Since its publication there has been a great increase in the importance of motor control, and many improvements have been made in its method and design. Each of the new developments is discussed in the present volume, which also incorporates those parts of the previous one which are still applicable. The new coauthor contributes the fruits of his long experience in control and application.

Among the subjects discussed is the electron tube, which has given engineers a new tool, first as a master switch to initiate control action, then as a converter to operate a d.c. motor from a.c. power and to control the motor voltage, as explained in Chap. XIX. So far such control is available only for small motors, but larger control seems practical at a later time.

Magnetic contactors are presented in Chap. IV. The deion principle or rupturing a.c. arcs is explained and its application is shown. The interlock details and the flexible shunt, which is now mounted to give long life, are also discussed.

The time-limit method of acceleration, which also gives forced acceleration, is now popular and is discussed in Chap. VI. It requires double overload protection—one element or device to permit short-time over-

loads but to protect against overheating, the other to open the circuit immediately if an excessive overload occurs. Some relays now combine these features (see Chap. XX). Magnetic time-delay acceleration and new types of dashpots for timing are both used. Some systems also include current limit. Another method makes use of the time required to charge or discharge a condenser. The tendency is to reduce the number of coils and interlocks as much as possible.

The development of plugging control is covered in Chap. IX. Various relay schemes are now available.

The motor-generator control of motor voltage is discussed in Chap. XI. The combination of a series generator with a series motor and means for adjusting the generator-field strength have made variable-voltage control available for small motors.

The development of the Regulex, the Ampledyne, and the Rototrol has provided new tools for regulating motor speed. These are described in Chap. XI.

Most squirrel-cage induction motors are started at full voltage, which has been made possible by larger power systems. Reduced-voltage starting, using series resistors, is simpler than the autotransformer starters but takes more current from the line. This question is analyzed in Chap. XVII.

Synchronized motors have a desirable influence on the power factor, and their control is simplified and made more rugged (see Chap. XVIII). New types of time-delay overload relays, which more nearly represent the time of heating the motor, are illustrated in Chap. XX and include some types mounted in the motor itself.

Recommendations for maintenance of control equipment are given in Chap. XXI.

The authors wish to express their appreciation for the assistance received from engineers associated with them and to thank the various manufacturers who so kindly furnished material for the illustrations.

H. D. James,
Lewis Edwin Markle.

Pittsburgh, Pa.,
April, 1945.

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CONTROLLERS FOR ELECTRIC MOTORS

CHAPTER I

FUNCTION AND TYPES OF CONTROL

THE FUNCTION OF CONTROL

The proper understanding of an electric controller requires that it be considered as a part of the motor; the controller should be designed to take care of the functions not incorporated in the motor design, in order to enable the latter to operate under the specified conditions of load. Every motor has certain inherent characteristics that enable it to adapt itself to some of the conditions encountered in practice. In many cases, however, the motor would be very expensive and also very inefficient if it were given the necessary characteristics to prevent its being injured or to prevent injury to the load during the cycle of operation. The functions usually supplied by the controller are as follows:

To Limit the Current during the Acceleration of the Motor.—The ohmic resistance of a motor is very low, so that when it is connected to the line while it is at rest a very large current would be drawn from the line if external resistance were not used to limit this current. As the motor accelerates it develops a counter e.m.f., which reduces the voltage available for causing a current to flow; hence the current is reduced. The current at any instant can be calculated by subtracting the counter e.m.f. from the line voltage, and dividing the result by the ohmic resistance in circuit (see Fig. 1). It is evident from the above that as the motor increases in speed the line current decreases (see Fig. 2) and the starting resistance may be reduced (see Figs. 3 and 4), until the motor is finally connected to the line without any external resistance. The short circuiting of this starting resistance can be done in several different ways.

Some d.c. motors are designed to be accelerated from rest, without the use of external starting resistance; these motors are, however, for use in particular applications. The squirrel-cage induction motor can also be started by connecting it directly to the line.

The motor armature is stationary when it is first connected to the line, and the current = volts ÷ ohms. The ohmage in the arma-

ture is very low, say 0.5 ohm; the total ohmage should be equal to volts ÷ current. Assume an e.m.f. of 230 volts and a current of 46 amp., $^{230}/_{46} = 5$ ohms. Then $5 - 0.5 = 4.5$ ohms external resistance. When the controller arm is on position 1 in Fig. 1, the current will be 46 amp.

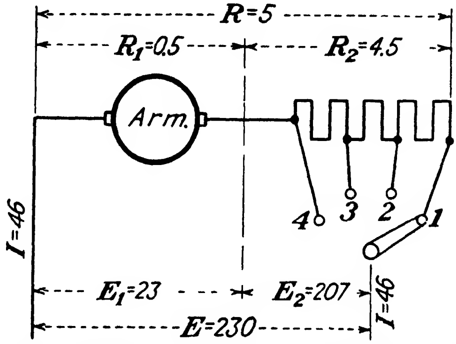


FIG. 1.—Voltage across the armature terminals when the armature is at rest and the circuit has been closed

When the motor armature revolves, it generates a counter e.m.f. (voltage). When this counter voltage is 50, the current will be

$$\frac{230 - 50}{5} = 36 \text{ amp.},$$

which is assumed as full load (Fig. 2) $36 \times 0.5 = 18$ volts drop through the armature resistance. Now move the controller to point 2

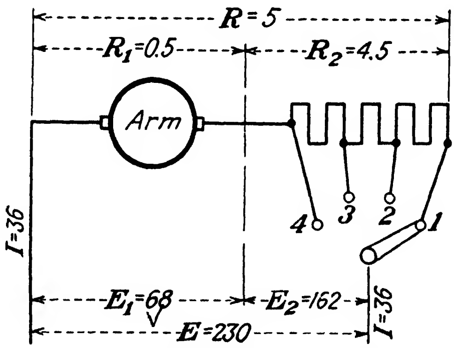


FIG. 2.—The motor has now accelerated until the torque is balanced by the load.

in Fig. 3 giving an external resistance of 3.5 ohms. The current now is $\frac{230 - 50}{3.5 + .5} = \frac{180}{4} = 45$ amp. This increased current will cause the motor to speed up until the counter voltage reduces the current to 36 amp.

The voltage drop in the external resistance is 3.5 × 36 = 126 volts. 230 − 126 = 104 volts across the armature. The controller is then moved to point 3 and then point 4, thereby bringing the motor up to full speed.

To Limit the Torque during Acceleration.—The torque of a motor is proportional to the current multiplied by the field strength. It is

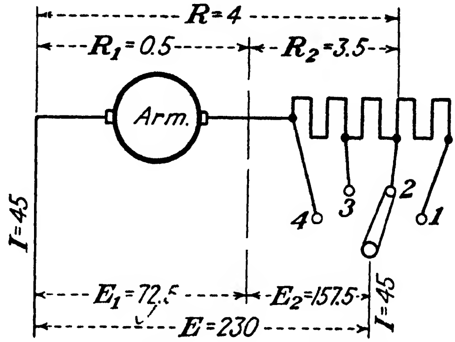
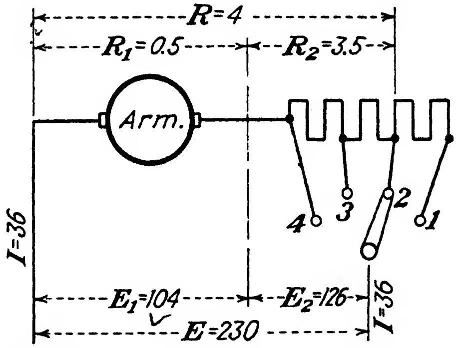


FIG. 3.—The controller is now moved to the second resistance step and the motor again accelerates.

often desirable to start a motor with a gradually increasing torque; this can easily be done with a shunt motor by starting it with zero field strength. The shunt field of the motor is connected to the line at the same time as the armature. Since it takes an appreciable time for the field to build up to full strength, the torque will increase gradually and



$E_h =$ 86 V

FIG. 4.—The motor has increased its speed until the torque is again balanced by the load.

give an easy start. In this way a shunt motor can be started with twice full-load current, or even greater current, and not cause a shock, or jar, to the motor or to the apparatus to which the motor is connected. A series or compound motor, started in the same way, will build up its torque much faster. The induction motor also builds up its torque rapidly. No motor, however, will build up its strength instantly, so

that it is not likely that any type of motor will give a hard shock to the machinery if it is started with zero field strength.

To Change the Direction of Rotation of the Motor.—In many classes of service the motor is required to reverse its direction of rotation repeatedly. It is a well-known fact that the d.c. motor can be reversed in rotation by reversing the current through the armature and keeping

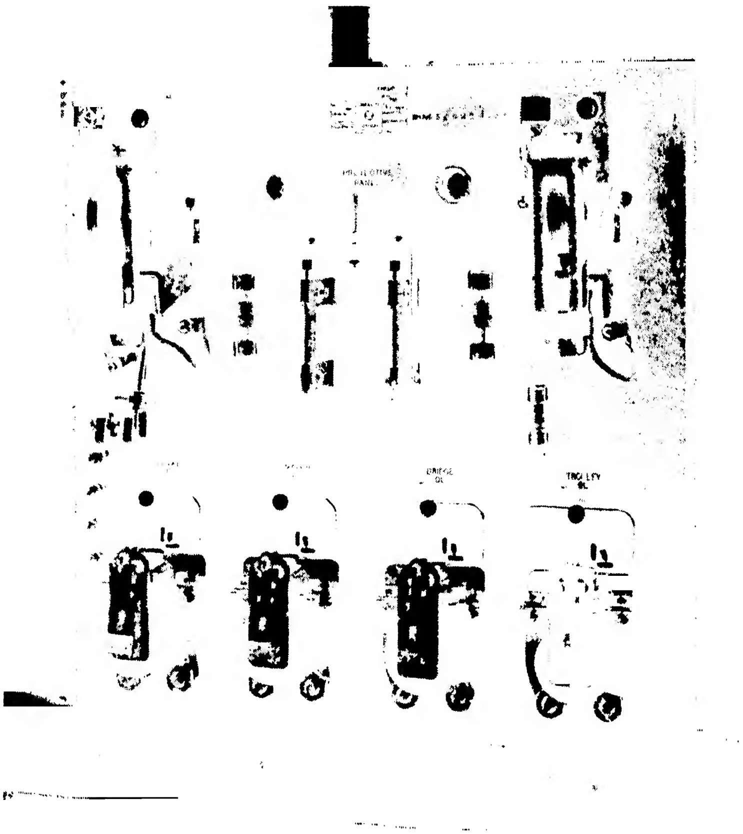


Fig. 5.—Crane protective panel showing overload relays with a time-element to delay the relays from opening the circuit.

the field in the same direction. The induction motor can be reversed by reversing one of the phases, and this is usually done by interchanging any two leads on a three-phase motor or interchanging the two leads in one phase of a two-phase motor. Where the motor operates continuously in one direction, these connections can be adjusted at the time of installing the motor, but where the reversal of rotation occurs frequently, some substantial form of reversing switch should be included in the controller.

To Limit the Load of the Motor.—This is usually done by means of fuses or a circuit breaker for manual control. Where the main-line switches are operated by magnets, an overload relay is used to deenergize the magnet and allow the switch to open. All overload devices should be provided with some form of time-element attachment. This will allow the motor to take a short peak load of a few seconds' duration without disconnecting itself from the line, which is very desirable, as such short-time peaks occur during acceleration and often during the normal operation of the motor.

Sometimes an overload relay is provided for inserting the starting resistance in the motor circuit in case of overload. This arrangement is required in special cases where it is undesirable to have the motor torque entirely cease. Such relays are sometimes called "jamming relays."

To Disconnect the Motor upon Failure of Voltage.—The voltage supply sometimes fails, and a serious injury might result upon the reestablishment of voltage if the motor were left connected to the line without the starting resistance. Manually operated starters and controllers are provided with a latch, held in place by a shunt magnet. This latch retains the controller in the running position. Upon the failure of line voltage, the catch is released and the controller is mechanically returned to the starting, or Off, position.

Magnetic contactor control automatically returns to the Off position upon the failure of line voltage, as the magnets are deenergized under such conditions. The controller can be connected so that it will automatically start the motor again upon the return of voltage to the line, in which case the circuit or device is known as "low-voltage release." Where it is necessary for the operator to perform some function, such as pushing a button after the failure of voltage, the circuit or device is known as "low-voltage protection." The latter is the one usually required, as an operator may be working on the machinery, and there is danger of its being started automatically and injuring him upon the return of voltage.

To Regulate the Speed of Rotation.—Frequently a motor is connected to a load requiring different operating speeds. This speed change can be effected in several different ways, the most common of which are as follows:

Armature Control.—Armature control (see Fig. 6) consists in putting resistance in series with the motor. Direct-current motors have this resistance in the armature circuit, and the voltage across the motor brushes is less than the line voltage, owing to the drop through this external resistance. Wound secondary induction motors are controlled in a similar way, by connecting the resistance in the secondary circuit (see Fig. 7). The drop in speed is in this case a little more complicated to calculate; the reduction in speed is proportional, however, to the

voltage drop through resistance. Motors controlled in this way are called "variable-speed motors." The speed at which the motor operates depends directly upon the torque required by the driven load. A change in torque causes a corresponding change in current, and the drop through the external resistance is equal to the current multiplied by the ohms.

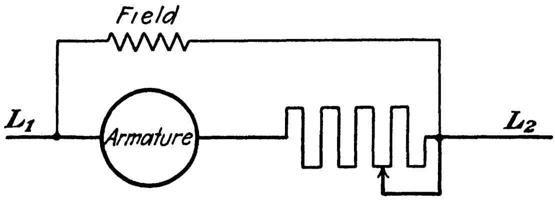


FIG. 6.—Direct-current motor with armature resistor.

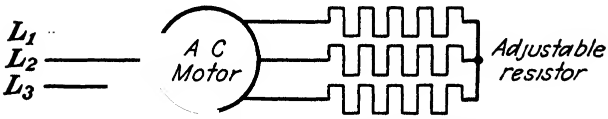


FIG. 7.—Alternating-current motor with secondary resistor.

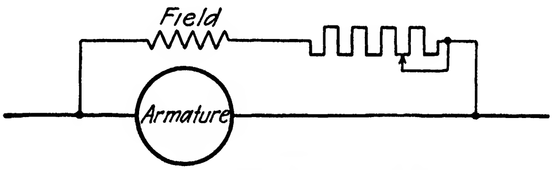


FIG. 8.—Direct-current motor arranged for changing the field strength.

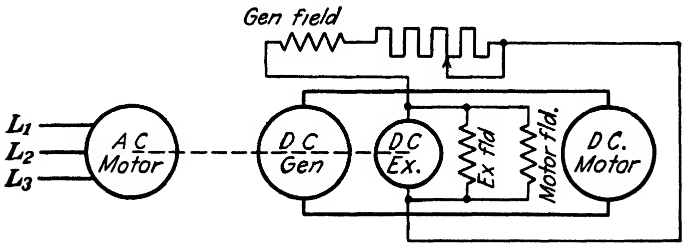


FIG. 9.—Method of changing the voltage of a d.c. motor by changing the generator field strength.

Changing the Field Strength.—In d.c. shunt motors changing the field strength varies their speed (see Fig. 8). This is usually done by connecting a rheostat in series with the shunt-field winding of the motor. Such motors are called "adjustable-speed motors," since the speed remains practically constant under all conditions of loading. Commercial motors of this type are built with speed ranges as high as four to one. At present no a.c. motors of this class are in commercial use.

Changing the Voltage of the Supply Circuit.—This also varies the speed of a motor (see Fig. 9). It is usually done by supplying each motor from a separate generator. This system of control is applied to elevators, mine hoists, reversing steel-mill motors, paper mills, machine tools, and many other motors (see Chap. XI).

To Start and Stop the Motor at Fixed Points in the Cycle of Operation, or at the Limit of Travel of the Load.—This feature can be obtained by the use of limit switches, which are operated by the machinery to which the motor is attached. They usually interrupt only a small circuit, thereby opening magnetic contactors, which, in turn, disconnect the main motor circuit. These limit switches may be connected by gearing to the driven machinery, in which case they are called "geared" limit switches. Where the limit switches are mounted along the runway, and operated by the machinery striking the switch, they are called "track," "stroke," or "hatchway" limit switches.

To Stop the Motor.—The motor can be brought to rest by either friction or dynamic braking (see Chap. IX).

Friction braking is accomplished by a mechanical brake, which is usually applied by a heavy spring and released by a magnet in series with the main circuit of the motor. In this case the brake is set whenever there is no current in the motor, and consequently no special arrangement is necessary on the controller to apply the brakes.

Dynamic braking requires at least one additional switch on the controller. It is accomplished by disconnecting the armature from the line and short-circuiting it on itself through a resistance with full field strength, the energy stored in the rotating parts being dissipated in heating the resistance.

To Protect the Operator from Injury.—It is very important to ensure the operator who uses the machinery against injury either during the starting of the motor or during the subsequent operation of the machinery. This requires the control apparatus to be properly protected, so that there is little danger of the operator's receiving a shock, or being burnt by an arc, in starting or during the operation of the machinery. Accidents may occur that require quick stopping of the machinery. To effect this result, safety stop devices are frequently placed around the machinery. They are operated either automatically or manually, depending upon conditions. These devices must be adapted to each particular application; but they are very important and should be carefully considered by engineers in specifying the electric drive.

THE CLASSIFICATION OF CONTROL APPARATUS

Electric controllers can be roughly divided into two general classes: manual acceleration and automatic acceleration.

Manual Acceleration.—This class comprises control apparatus in which the acceleration of the motor is entirely under the control of the operator. Illustrations of this are the faceplate- and drum-type controllers.

Automatic Acceleration.—This class comprises control apparatus in which the acceleration of the motor is performed automatically.

These terms are usually applied to the method of acceleration. Controllers may have a combination of these two methods; for example, a magnetic contactor type of crane controller may have a master switch with five or six notches. The acceleration between notches is automatic, but the operator can determine the direction of rotation and the speed of the motor. The rate of change in speed, however, is automatic.

Controllers, including starters, may be divided into the several groups given below. These groups do not include every type that is built, but they give a good idea of present practice. The advantages and limitations listed must be interpreted in a very general manner, as they may not apply in many special cases. The magnetic contactor controller is usually automatic. The other types are generally manual; but automatic acceleration may be obtained by using an electric motor or an air cylinder to operate them.

Faceplate Controllers
(Fig. 15)

Advantages

1. Low in price.
2. Compact, usually with self-contained resistor.
3. Easy to mount on wall or switchboard.
4. Flexible in design, can be readily altered.
5. Inexpensive, as to renewals of contacts and repairs.
6. Low-voltage protection feature easily applied.

Limitations

1. Design usually not well adapted to taking care of arcing. For this reason it is not good for heavy or frequent service.
2. Design usually not rugged mechanically.
3. A type that presents difficulties where the connections are complicated, such as a reversing control for wound secondary motors.

Drum Controller (Cylinder Type)
(Fig. 10)

Advantages

1. Low in price in small and medium sizes.
2. Compact, but with separately mounted resistor.
3. Entirely enclosed. Can be made dustproof, sprayproof, or gasproof.
4. Strong mechanically and simple to operate.
5. Capable of having various mechanical retarding devices attached to prevent too rapid acceleration.

6. Capable of having complicated connections made; *i.e.*, forward and reverse, or power and brake, on the same drum.

Limitations

1. Modification of design, difficult and expensive.
2. Frequent inspection and adjustment of contacts necessary.
3. Rapid deterioration of contacts under severe conditions.
4. Care of the energy of the arc, sometimes difficult.
5. Limitation as to size.
6. Large sizes, difficult to operate.

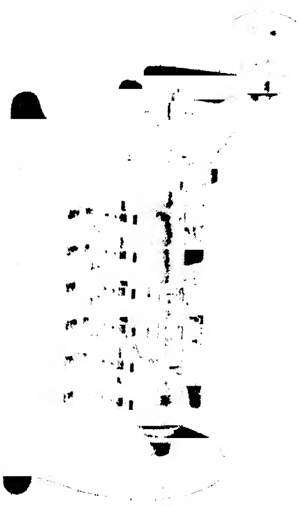


FIG. 10.—Drum controller with cover removed.

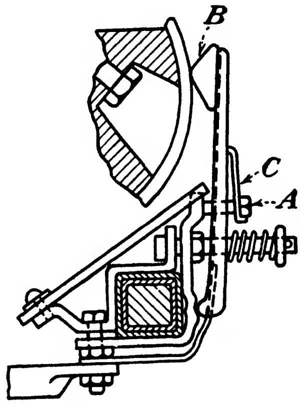


FIG. 11.—Drum controller, sectional view, showing the sliding contact made between the finger *B* and the drum cylinder.

CAM CONTROLLERS (MANUALLY OPERATED)
(Fig. 12)

Advantages

1. Low in price.
2. Compact in design, but with resistor separately mounted.
3. Entirely enclosed. Can be made dustproof, sprayproof, or gasproof.
4. Strong mechanically and simple to operate. Can be provided with reciprocating as well as rotating handle.
5. Capable of having various mechanical retarding devices attached to the handle to prevent too-rapid acceleration.
6. Capable of having complicated connections made readily.
7. Capable of having new combinations made easily by changing the number of units and the shape of individual cams.
8. Rolling contacts used, which are usually free from welding.
9. Contacts, easily and cheaply renewed.
10. Entire unit can be replaced if necessary.

11. Easy to inspect.
12. *Quick closing and opening not found in drum controllers*
13. *Combining the simplicity of the manual controller with the durability of magnetic control.*

Limitations

1. The larger sizes require more power to operate than does a master switch.
2. On account of the enclosure the continuous capacity may be reduced and the energy of the arc must be limited.
3. There are limitations in size.

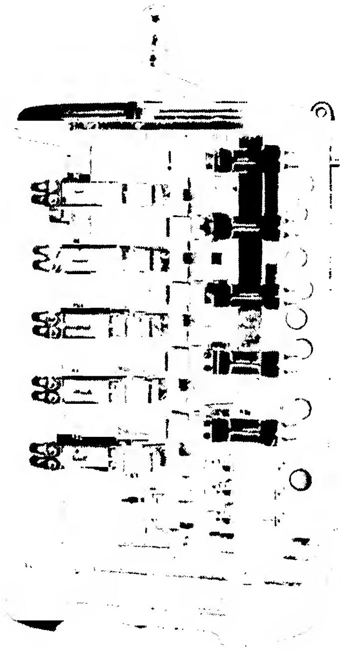


FIG. 12 – Cam controller with the cover removed.

MAGNETIC CONTACTOR CONTROL
(Fig 13)

Advantages

1. Long life of contacts because of the rolling action and a quick opening and closing.
2. Positive opening and closing of contacts
3. Flexibility in adapting controller to various designs.
4. Can be arranged with various safety attachments.
5. More foolproof than other types.
6. Strong and rugged mechanically.
7. Automatic control can be obtained.
8. Contacts are easily and cheaply renewed.

9. Entire unit can be replaced if necessary.
10. Inspection easy.
11. A saving in copper connections, as the controller can be located close to the motor, and the master switch wherever convenient.
12. A time element in closing and opening, not found in drum controllers.

Limitations

1. More expensive than manual controllers.
2. The larger sizes occupy considerable space.
3. The wiring diagram is complicated.

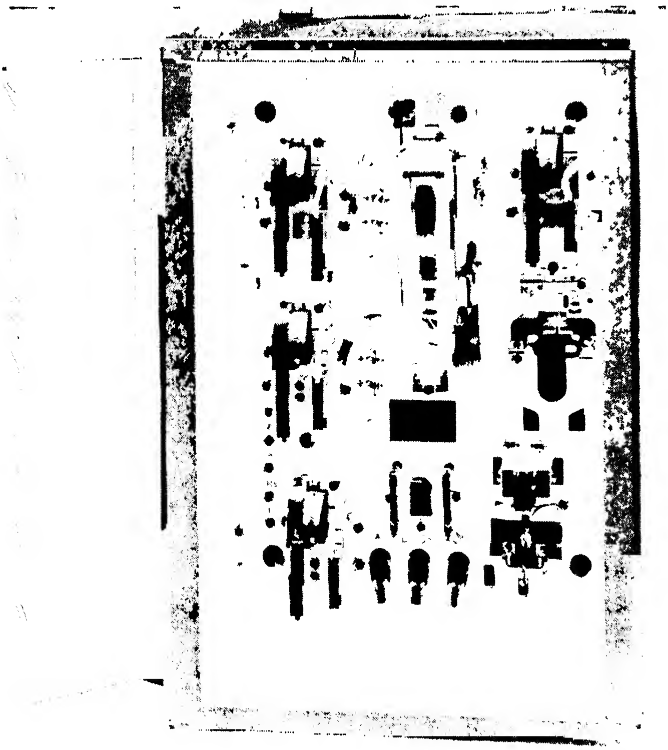


FIG. 13. – Magnetic contactor controller with door of cabinet open.

LIQUID CONTROLLERS
(Fig 245)

Advantages

1. Large thermal capacity for starting.
2. Very gradual change of resistance.
3. Absence of arcing or other wear, as no contacts are used (except line switch).
4. The resistance can be easily adjusted by varying the amount of soda in the solution.
5. It can be readily adapted for automatic operation.

Limitations

1. Considerable floor space is required.
2. The electrodes are subject to corrosion.
3. Cooling water is required for the larger sizes.
4. The use of the liquid limits its application.

In specifying control apparatus, the following information should always be included.

1. The characteristics of the power circuit, such as voltage, frequency, number of phases, voltage regulation, should be given.
2. A brief description of the control apparatus required should be included.
3. If the motor speed is to be adjusted, the speed range should be given, the load at the maximum and minimum speed and the number of speed points.
4. The cycle of operation should be stated in detail, particularly the number of starts made by the motor per hour.
5. A description should be given of the machine that the motor drives, particularly the torque required to accelerate to full speed.
6. A description of any unusual features of the installation, such as moisture, dust, acid fumes, limited source of power, space available for the apparatus, etc., should be noted.
7. Complete rating (nameplate reading of the motor) should be given.

All this information is necessary for the intelligent selection of both the motor and the control. In the absence of any of this information, the engineer furnishing the electrical apparatus must guess at the requirements on the basis of the best average practice. This will often take care of the situation, but exact information is very much better.

CHAPTER II

HOW TO READ CONTROLLER DIAGRAMS

A controller diagram consists of a group of symbols joined together by lines that represent wires; the symbols represent the motor and the controller elements. It is a sign language used to express the functioning of the control system.

The symbols and terminal markings used in this book are listed on page 30. Some of these symbols are more elaborate than those used on manufacturers' diagrams because they require less imagination to understand and are, therefore, easier to read. After anyone has become experienced in reading diagrams, he can understand any reasonable symbols.

The present discussion is intended to deal, in an elementary manner, with a few simple forms of controllers, with the intention of explaining some of the fundamental principles of operation. A thorough understanding of this section will be of material assistance in the consideration of subsequent discussions of more complicated forms of controllers as they are used in various industries.

FACEPLATE CONTROLLERS

The faceplate controller is the simplest type used for starting or regulating the speed of an electric motor. Figure 14 illustrates the elements of this controller. While this arrangement is operative, commercial apparatus usually has additional features, which in this instance are omitted for the purpose of clearness. $L+$ and $L-$ represent the two power wires leading to the controller and a compound-wound motor. If the rheostat arm be moved from the Off position, shown in the diagram, to the contact R_1, current will flow from $L+$ to the arm, from this to contact R_1, through the regulating resistance to R_{10}, thence through the armature and series field of the motor to $L-$. The shunt field is connected from R_1 to $L-$, and is energized as soon as the rheostat arm makes contact with R_1. The voltage across the armature will be equal to the line voltage minus the voltage drop through the regulating resistor. The torque of the motor will be proportional to the armature current and the field strength. When the contact is first made at R_1 the field strength is zero; it takes a short interval for the field to reach its full value, so that under ordinary conditions the torque will increase from zero to a value that will start the motor. The rotation of the armature in

the motor field generates a voltage known as the counter e.m.f. which opposes the line voltage. As the motor increases in speed, the difference between the line and counter e.m.f. becomes less and the motor current decreases until a balanced condition is reached. When this balancing condition is reached, the speed of the motor may be further increased by moving the rheostat arm to contact R_2. Additional increments of speed are obtained by additional movements of the arm to other contacts until all of the regulating resistance is eliminated from the circuit and the arm *rests* on contact R_{10}. The arm should be allowed to remain on each contact until the motor reaches its balancing speed for

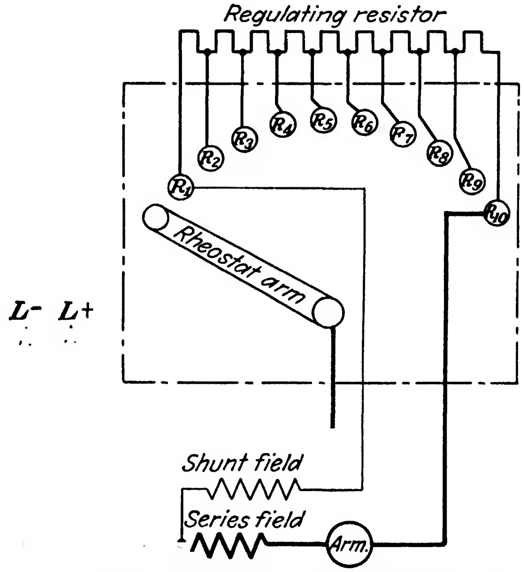


FIG. 14.—Elementary controller with face-plate rheostat.

that step of the resistance, so that the minimum amount of current will be taken by the motor.

In bringing the motor to rest, the reverse operation of the arm is made. In passing from contact R_1 to the Off position, the connection between the motor and $L+$ is interrupted, causing the motor to come to rest. The shunt field, however, will still be connected across the armature of the motor, including the regulating resistor. This connection should be used wherever possible, as it allows the field current to die down gradually as the speed of the motor decreases. The drop in voltage through the starting resistor, with only the field current flowing, is so small that it may be neglected and the field can be considered as having a voltage equal to the counter e.m.f. of the motor. The shunt-field winding consists of a large number of turns of fine wire. Any change in the

value of the field current is opposed by the self-induction of this winding, so that a change in the current should be made gradually. If an attempt is made to open the field circuit abruptly, the self-induction will cause a high voltage to build up between the terminals of the field coils, which may result in the breaking down of the insulation.

If the rheostat is to be used for starting purposes only, the resistor is made of less current-carrying capacity than that needed for regulating purposes. It is called a "starting rheostat," or a "regulating rheostat," depending upon the purpose for which it is used. The connections,

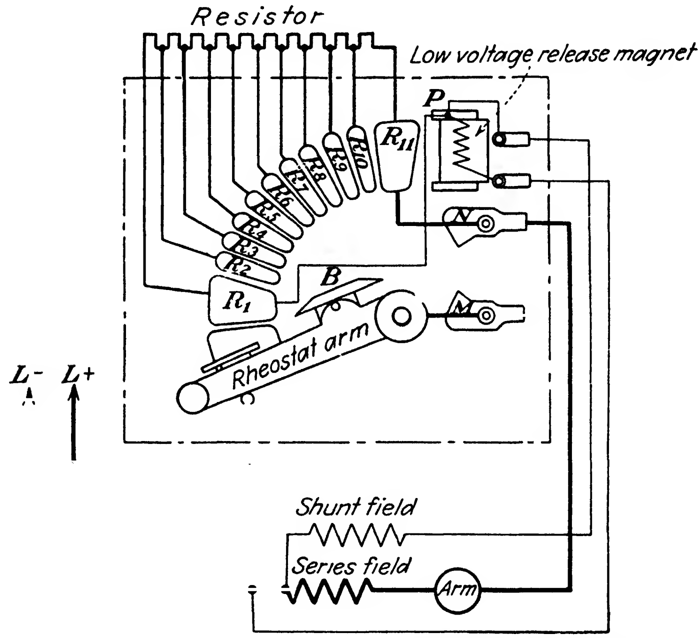


FIG. 15.—A commercial controller using a starting rheostat.

however, are the same, the difference being only in the capacity of the resistor. A commercial design of starting rheostat is shown in Fig. 15. This rheostat differs from the one previously described, in the addition of the low-voltage release magnet. The rheostat arm is provided with a spring, which returns it to the Off position if the handle is released during the starting of the motor. After the motor has been brought up to speed and the rheostat arm rests upon contact R_{11}, the low-voltage release magnet holds the arm in this position. Brush T bridges between the terminals M and N, so that in the running position the current passes from $L+$ to terminal M, through the brush B to terminal N, thence to the armature of the motor and through the series field to $L-$. This provides a circuit parallel to the one through the rheostat arm to contact

R_{11}, so that the continuous flow of current will not overheat the rheostat arm and its contacts. In the running position, the rheostat arm is held firmly by the low-voltage release magnet, so that current flows from $L+$ through the rheostat arm to point P on the magnet. One circuit then passes through the magnet winding to $L-$. The other circuit is connected to the shunt field. If, for any reason, the line wires are disconnected or the voltage on the circuit fails, the low-voltage release magnet will be deenergized and the spring will return the rheostat arm to the starting position.

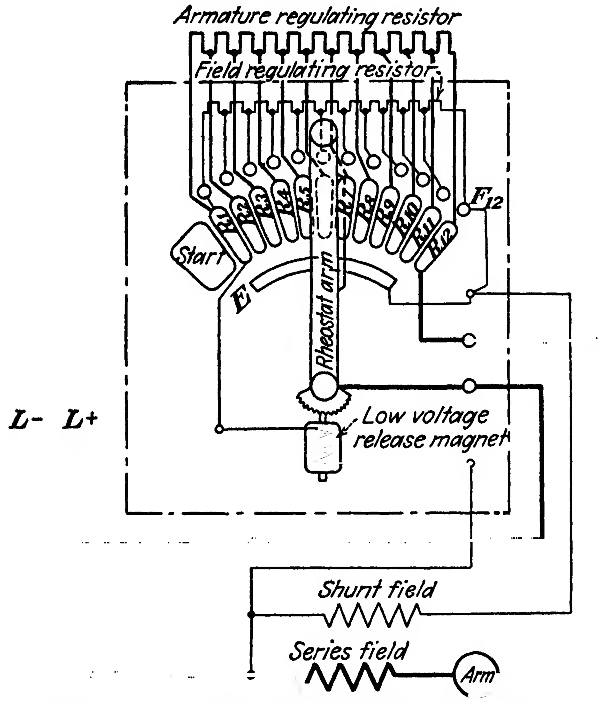


FIG. 16.—A starting and speed regulating rheostat having both armature and field resistors.

A controller provided with both armature- and field-regulating resistance is shown in Fig. 16. The motor is known as an adjustable-speed motor and can have its speed changed by adjusting its field strength. The rheostat arm is made in two parts, the under part making contact with the segments marked R_1 to R_{12} and with the contact ring E, while the top arm engages the upper row of round contacts. When starting, the two arms are held together by a latch. The bottom arm is provided with a notched segment engaging a plunger forming part of the low-voltage release magnet. The notched segment and the pawl hold the arm in any operating position after the low-voltage magnet is energized.

To start the motor, the contact arms are moved from the Off position to contact R_1. The current flows from $L+$ through the arm to contact R_1, thence through the armature-regulating resistor to contact R_{12}, and then through the armature and series field to $L-$. The shunt-field current flows from $L+$ through the arm to the segment E, to the field windings, and thence to $L-$. Connected with R_1 is a shunt circuit passing from the positive side of the line through the low-voltage release magnet to the negative side of the line. The arms are gradually moved to the right, eliminating successively each section of the armature resistor until the bottom arm makes contact with R_{12}. In this position the armature is connected directly across the line and the segment E is disconnected from the rheostat arm. The shunt-field circuit now is from the positive side of the line through the upper rheostat arm to the right-hand field contact F_{12}, thence to the field winding. This gives a motor speed corresponding to full field strength If it is desired to increase the speed of the motor, the upper arm can be moved to the left across the field contacts to insert resistance gradually in the shunt-field circuit and thus within its range give the increased speed required, while the low-voltage release magnet holds the lower arm on contact R_{12}.

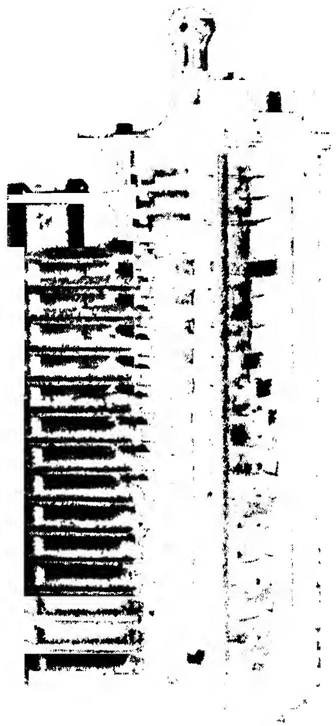


FIG 17 —Drum controller with cover removed and arc boxes rotated away from the contacts

If the circuit is interrupted, the low-voltage release magnet will allow the lower arm to be carried to the off position by means of its spring. It, in turn, picks up the upper arm and the two are moved quickly to the Off position.

DRUM CONTROLLERS

A drum type of controller is shown in Fig. 17. Such a controller consists of two rows of contact fingers attached to the framework of the controller, but insulated from it so as to be electrically separated from each other. Between these rows of fingers is mounted an insulated

cylinder, or drum, which is revolved by the handle. On this drum are mounted copper segments of different lengths, which engage the contact fingers. The length and location of these segments are such as to make different connections for each "notch" of the controller. Attached to the drum shaft at the top is a wheel having notches corresponding to each of the operating positions of the controller handle. A roller is forced into one of these notches by a spring whenever a set of contacts is properly engaged, thus indicating to the operator the correct running positions of the controller and preventing motion from any of these positions, due to vibration or other accidental means. Figure 18 shows

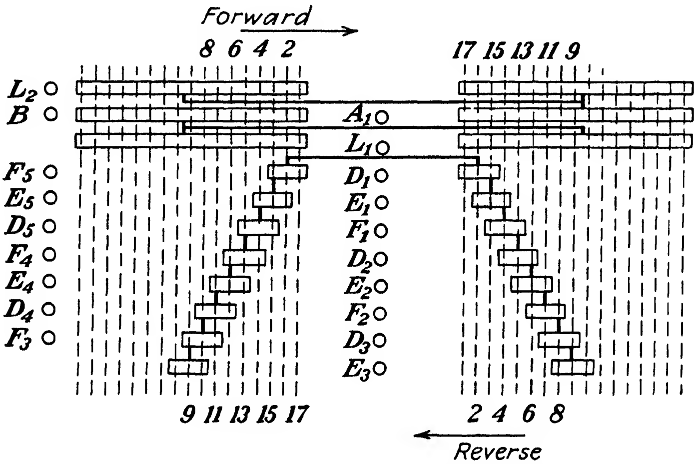


FIG. 18.—Diagrammatic representation of a drum switch and its contact fingers rolled out flat. (See Fig. 20 for a complete diagram.)

the segments of such a drum as they would appear if rolled out flat. The two vertical rows of circles represent the stationary contact fingers. The horizontal strips represent the segments of the rotating drum, and the vertical dotted lines show the position of the segments with respect to the controller fingers at each successive position of the drum.

A slip-ring motor control arrangement with the controller connected only to the secondary circuit of the motor is shown in Fig. 19 with the drum rolled out, or "developed," as in Fig. 18. When the primary of the motor is connected to the power line, current passes through the secondary wires and thence through the resistor, completing the circuit. When the motor is at zero speed the controller drum should be in position 1. If the cylinder of the drum is now moved from right to left, the dotted line 2 travels over to the center line of the contact fingers and the resistor section E to E_1 is short-circuited, decreasing the resistance in part of the secondary circuit of the motor. As the speed of the motors

increases, a further movement of the drum will cause the vertical line 3 to intersect the contact fingers. This will short-circuit the resistor section from D to D_1. At each increase of the motor speed a further movement of the drum may be made until the vertical line 13 intersects the controller fingers. In this position all of the resistor is short-circuited and the motor is operating at full speed.

A drum-controller diagram similar to that shown in Fig. 19, except that it provides for reversing the direction of rotation of the motor, is

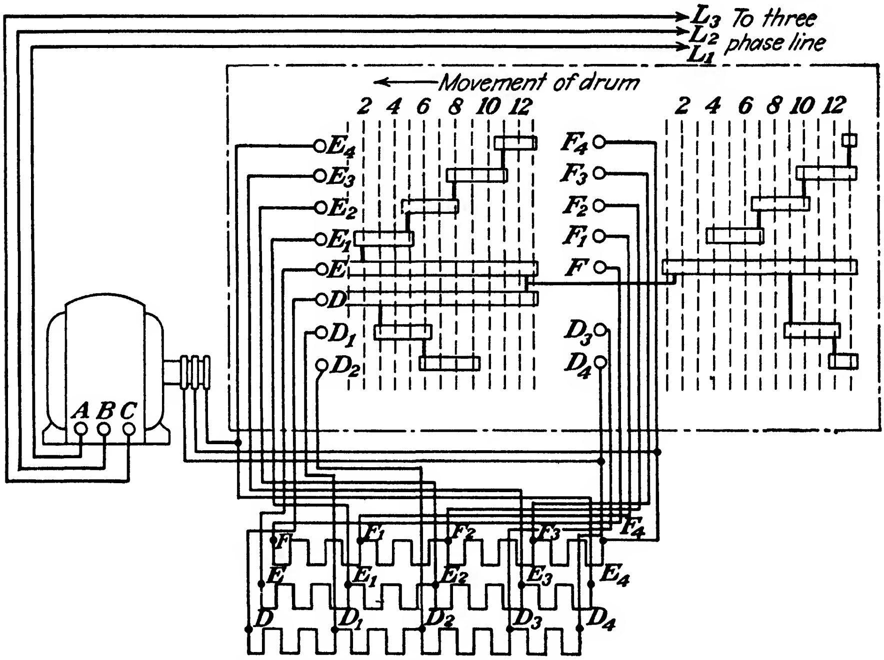


FIG. 19.—A nonreversing controller for a three-phase, wound-secondary, induction motor showing the resistors and drum development.

given in Fig. 20. One motor terminal marked C is connected directly to the line. The other two terminals of the motor, marked A and B, are connected to correspondingly marked terminals of the controller. In the forward direction, the drum segments on the right-hand side of the diagram move toward the left-hand row of fingers, and the segments on the left-hand side of the diagram move toward the middle row of fingers. This will be understood if the developed diagram showing the drum contacts is replaced so as to fit on the surface of a cylinder, or drum, and the contact fingers marked on two vertical sticks of wood mounted on each side of the cylinder 180 deg. apart. When the drum segments are moved from left to right for forward operation, the terminal A of the motor is connected through finger A_1, and the second and third segments

from the top, which are connected together as indicated, to L_1 power wire. Likewise, the terminal B of the motor is connected to L_2 power wire.

The arrangement of the drum contacts for short-circuiting the secondary resistors differs somewhat from that shown in Fig. 19. The first notch in the forward direction closes the contacts to the primary of the motor A to L_1 and B to L_2. A drum segment is brought in contact with the finger marked D_1 on this notch, but as no other connection is made

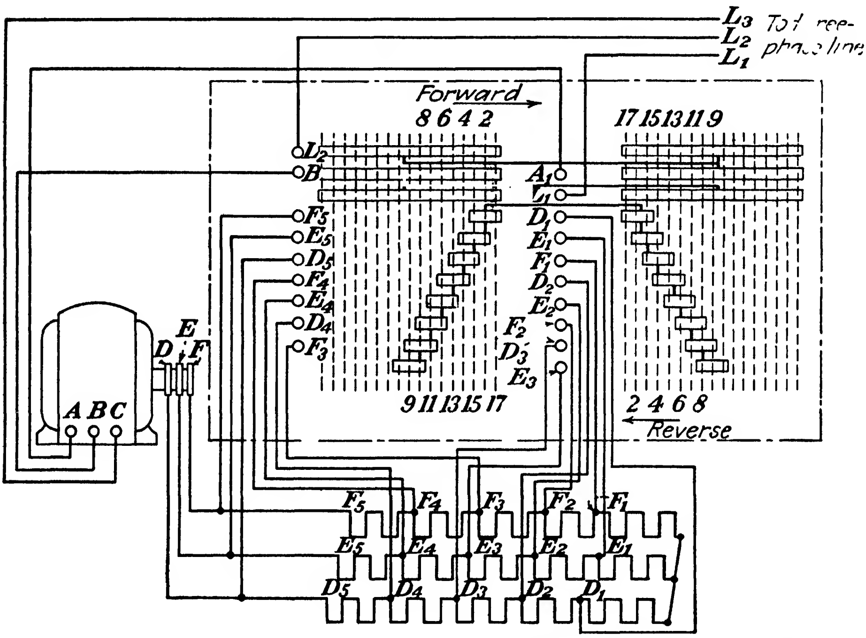


FIG. 20.—A reversing controller for an a. c., wound-secondary, induction motor. The drum development alone is shown in Fig. 18.

to the resistors this contact causes no change in the secondary resistance. The motor, therefore, starts to rotate at its minimum speed with all resistance in the secondary. When the drum is moved over until the dotted line 2 intersects the central row of fingers, the one marked E_1 is connected to the drum, short-circuiting the section of the resistor between D_1 and E_1. Next the dotted line marked 3 intersects the central row of fingers and F_1 is connected to the drum, short-circuiting another section of the resistor. This sequence is continued until the dotted line 8 intersects the central line of fingers connecting E_3 to the drum. A further movement of the drum causes the dotted line 9 in the right-hand part to intersect the left-hand row of fingers connecting resistor F_3 to the drum. The dotted lines 10 to 15 successively intersect the left-hand row of fin-

gers, gradually short-circuiting all of the resistor, which brings the motor up to full speed.

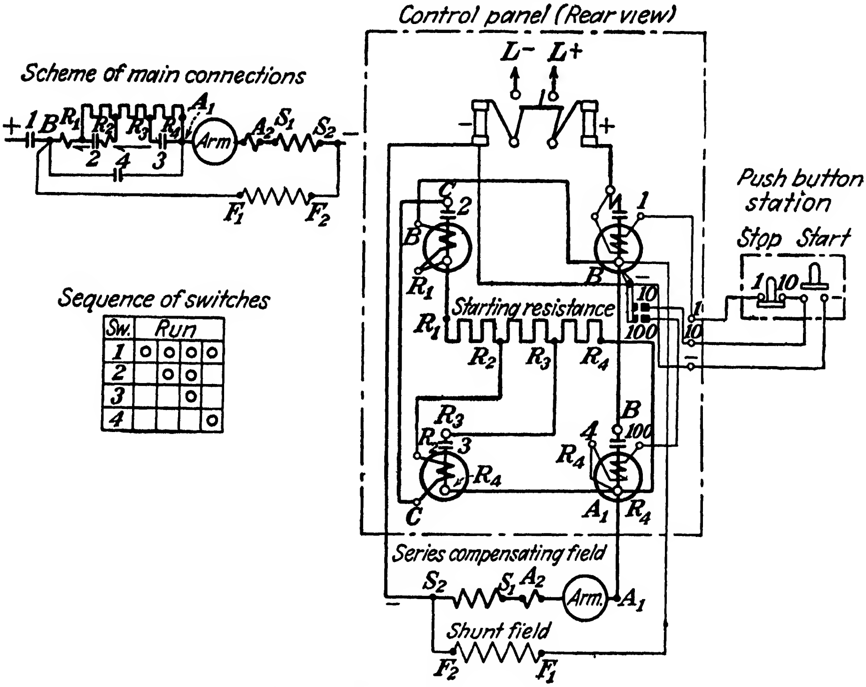
The reverse direction of operation causes the drum segments to move from right to left. In this case the left-hand dotted lines are brought into contact with the left-hand row of fingers and the right-hand row of dotted lines into contact with the middle row of fingers. The primary terminal A of the motor is connected to line L_2 and the terminal B of the motor line L_1, when the dotted line 1 intersects the middle row of fingers. A further movement of the drum from right to left causes the dotted lines 2 to 8 to intersect successively the central row of fingers. This short-circuits a part of the starting resistors. Further movement of the drum from right to left causes the contact shown on the dotted line 9 to intersect the finger F_3. A further movement brings the dotted lines 10 to 15, inclusive, so that they successively intersect the left-hand row of fingers. This short-circuits all of the resistor and brings the motor up to speed in the reverse direction.

MAGNETIC-CONTACTOR CONTROL

In a simple starter of the magnetic-contactor type, the controller consists of a panel, at the top of which are mounted a knife switch, with two fuses for overload protection, and four contactors underneath. A contactor is a switch that is held in the Open position by gravity and closed by a magnet. Contactor 1 (see scheme of main connections in Fig. 21) is provided with a blow-out coil, because of opening and closing the main motor circuit. Contactors 2, 3, and 4 are used for short-circuiting the starting resistor sections, which are mounted in the rear of the panel. This arrangement is shown diagrammatically in Fig. 21, with a scheme of main connections at the left. At each point where the circuit is broken by two small parallel lines is a contactor. The numbers opposite these parallel lines are the same as those shown in the main diagram. The single loops represent the series coils for contactors 2 and 3. An arrow is drawn between the parallel lines representing these switches and the loop representing the coil for each particular contactor. Underneath this scheme of main connections is shown a table called "Sequence of switches." This table has four vertical rows, in which circles are drawn. The first row represents the first starting position of the controller, and the last row the running position of the controller. Where a circle is shown opposite a switch number it indicates that that contactor is closed. This table is used as follows:

In the first vertical column, opposite 1, is shown a circle that indicates that the contactor 1 is closed. This operation connects the shunt field of the motor from the point B to the negative side of the line. This arrangement of shunt-field connections is the same as was previously

explained. Now refer to the schematic diagram and trace the main current from the positive side of the line through contactor 1 and the coil of 2, to R_1 of the resistor, through this resistor to the A_1 terminal of the motor, through the motor armature and series field, to the negative side of the line. Referring again to the table, it can be seen that in the second column contactor 2 also is closed, the path of the current being from the positive side of the line through 1 and 2 contactors, the coil of contactor 3, to R_2 on the resistor; from there it follows the same path as that for the first column. The third column of the table shows



Sw.	Run			
1	o	o	o	o
2		o	o	
3			o	
4				o

FIG. 21.—Connections of a magnetic contactor controller with three starting steps.

that contactor 3 is closed. The current now passes to R_2, as has been previously described, through one section of the resistor to R_3, from here to A_1 on the motor armature, and through the armature and series fields to the negative line. The fourth column of the table shows that contactors 1 and 4 only are closed. The path of the current then is from the positive line through switch 1 to B, then through switch 4 to A_1, through the armature and series field to the negative line. This connects the motor directly to the line, without any external resistance, and is the full-speed position of the controller.

In the main diagram, the magnetic contactors are represented by circles and the operating coils are shown inside the circles. The moving

contact is represented by the bottom of the two parallel lines. The upper parallel line is the stationary contact connected to the upper terminal of the switch. When the coil is energized sufficiently to attract the armature, the two parallel lines are brought together and current can flow between the top and bottom terminals of the switch. Underneath contactor 1 is a small switch, indicated by square dots, and a pivoted arm. When 1 is open, this auxiliary switch, known as an "interlock," is also open. The two contacts connected to the arm of this interlock are joined together electrically and to the hinge joint, so that they complete the circuit between the stationary contacts 10 and 100 and the pivot, when 1 closes. To the right of the diagram is a rectangle enclosing two push buttons. The button marked Start is held in the open position by a spring and the Stop button is held in the closed position by a spring. If the Start button is depressed for a moment, current flows from the positive line through the knife switch and fuse to the coil of switch 1, through this coil to the terminal 1 of the Stop button, to terminal 10 and through the Start button, fuse, and knife switch, to the negative side of the line. This energizes the coil of contactor 1 and closes the main contact. This coil is now connected from terminal 1 through the Stop button to terminal 10 on the interlock underneath this switch to the negative side of the line, which makes the circuit to the coil 1 independent of the Start button, so that this button may now be released. The current now passes from the positive side of the line through the contact 1 and across to terminal B on 2, through the coil of this contactor to R_1, through the starting resistor to R_4, thence to the bottom terminal of 4 to A_1 on the motor, through the armature and series field of the motor to the negative side of the line. As the motor increases in speed, the current through the coil of 2 decreases until this contactor closes.

A contactor operates on what is known as the "lockout" principle, *i.e.*, it closes when its current is below a set value and above another much lower value. When 2 closes, it short-circuits one section of the starting resistor from the terminal R_1 through the contact on 2 to the terminal C, through the coil of 3 to R_2 on the resistor. This again increases the current of the motor and prevents 3 from closing until the current has decreased to a fixed value. When 3 closes, it short-circuits the section of the resistor between R_3 and R_4. This leaves the resistor section between R_2 and R_3 in series with the motor. The coil of contactor 4 is in shunt across the armature of the motor. The circuit is from A_1 through the coil to terminal 100 on the interlock underneath 1, through this interlock to the hinge joint, which is connected to the negative line. Since the A_2 terminal of the motor armature is connected to the negative side of the line, the voltage across this coil is equal to the counter e.m.f. of the motor. When the speed of the motor reaches

the proper value, contactor 4 closes, connecting the A_1 terminal of the motor directly to $L+$ through the contact on 1.

To stop the motor, push on the button marked Stop, thus opening the circuit between terminals 1 and 10, and disconnecting the operating coil of contactor 1 from $L-$. This opens contactor 1 and disconnects the motor from the positive line. The opening of switch 1 opens the contacts 10 and 100 on the interlock underneath, thus disconnecting the coil of contactor 4 from its motor-armature circuit and leaving the equipment ready for operation again.

CHAPTER III

HOW TO MAKE CONTROLLER DIAGRAMS

Skill and experience are required to make a clear, readable diagram. This is particularly true of the more complicated diagrams of automatic controllers. For the making of such diagrams, experience has revealed a number of features that should be considered, most of them based on existing practice that has developed with the art. A definite plan and method of procedure should be worked out for each diagram.

In order to classify the different types of diagrams the National Electrical Manufacturers Association adopted the following definitions.

Controller Wiring Diagram.—A diagram showing the electrical connections between the parts comprising the controller, and indicating the external connections.

External Controller Wiring Diagram.—A diagram showing the electrical connections between the controller terminals and outside points; such as connections from the line to the motor, and to auxiliary devices.

Controller Construction Diagram.—A diagram indicating the physical arrangement of parts, such as wiring, buses, resistor units, etc. Example: A diagram showing the arrangement of grids and terminals in a grid-type resistor.

Elementary Controller Diagram.—A diagram using symbols and an elementary plan of connections to illustrate, in simple form, the motor circuits and the scheme of control.

Control Circuit Line Diagram.—A diagram showing in simple form the path of each branch of the control circuit from line to line.

Control Sequence Table.—A table indicating the connecting devices that are closed for each successive position of the controller.

Several of these diagrams are illustrated in order to make the definitions more easily understood. It is desirable to have a definite name for each kind of diagram, in order that engineers may better understand each other in discussing questions. In adopting these definitions the Electrical Manufacturers considered all of the names commonly used for these different diagrams and formulated names and definitions which seemed the most logical to describe particular diagrams. We will now proceed to make some diagrams.

The diagrams for manual controllers, such as drum controllers and face plate control, are the simplest. Typical diagrams are shown in Figs. 14, 15, 22–25. Often the complete diagram can be made up without first making an elementary controller diagram.

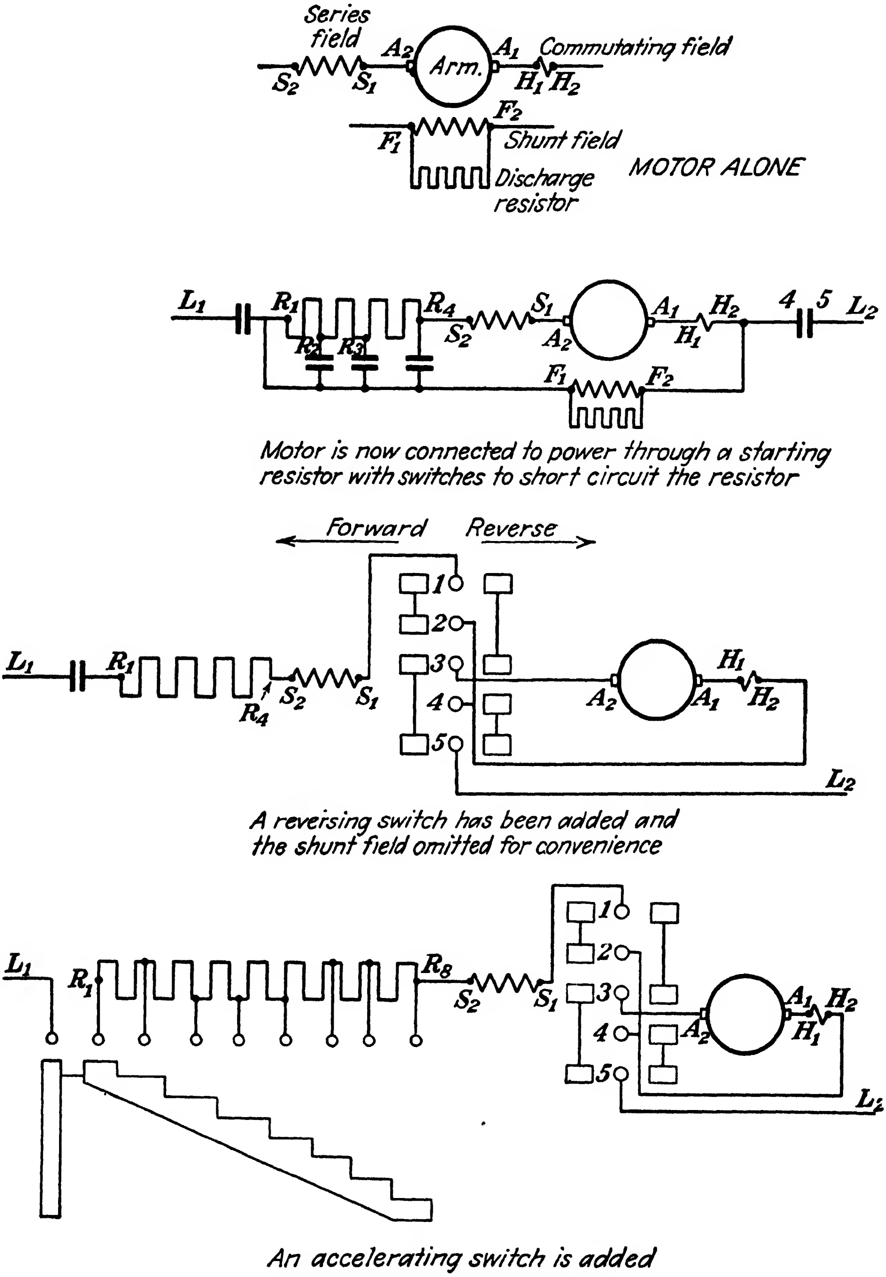


FIG. 22.—Steps in the development of the diagram shown in Fig. 23.

Diagrams for automatic control using magnet contactors can best be made up by first working out the elementary diagrams in the following order, using the symbols shown in Fig. 26.

1. Make an elementary controller diagram (definition 4, Fig. 27).
2. Make a control sequence table (definition 6, Fig. 28)
3. Make the control circuit line diagram (definition 5, Fig. 29).
4. Make the complete controller wiring diagram (definition 1, Fig. 30).

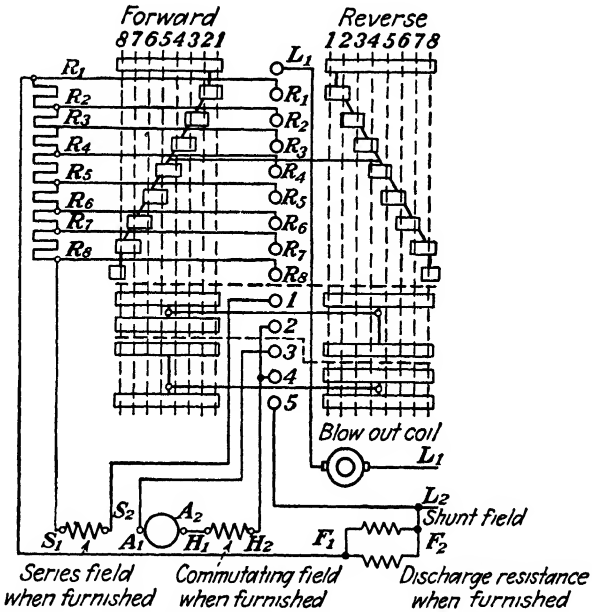


FIG. 23.—Diagram of a reversing drum controller with magnetic blowout for a d.c. motor.

If the controller is complicated, it may be desirable to make an external wiring diagram (definition 2). If the controller is for a large motor, where a heavy bus structure is necessary for carrying the current, it may be necessary to make a controller construction diagram.

DESIGNATIONS

All contactors, relays, coils, interlocks, etc., should be marked. The following markings are used in this book.

Contactors: 1 and 3—Forward or up. 2 and 4—Reverse or down. 5 and 6—Line contactors (use No. 5 with reversing d.c. controller). 7 to 10—Other main switching purposes. 11 to 20—Direct-current armature series resistance contactors and contactors in wound-rotor induction-motor secondary circuits, used for starting and regulating. 21 to 30—Armature shunt and dynamic braking contactors. Back contact—Number followed by *A*.

On d.c. double-pole contactors and a.c. primary contactors, each contact should have a different number, as required by the standard marking. Accelerating contactors should be numbered in the order in which they close, *i.e.*, No. 11 closes first; No. 12, second; etc.

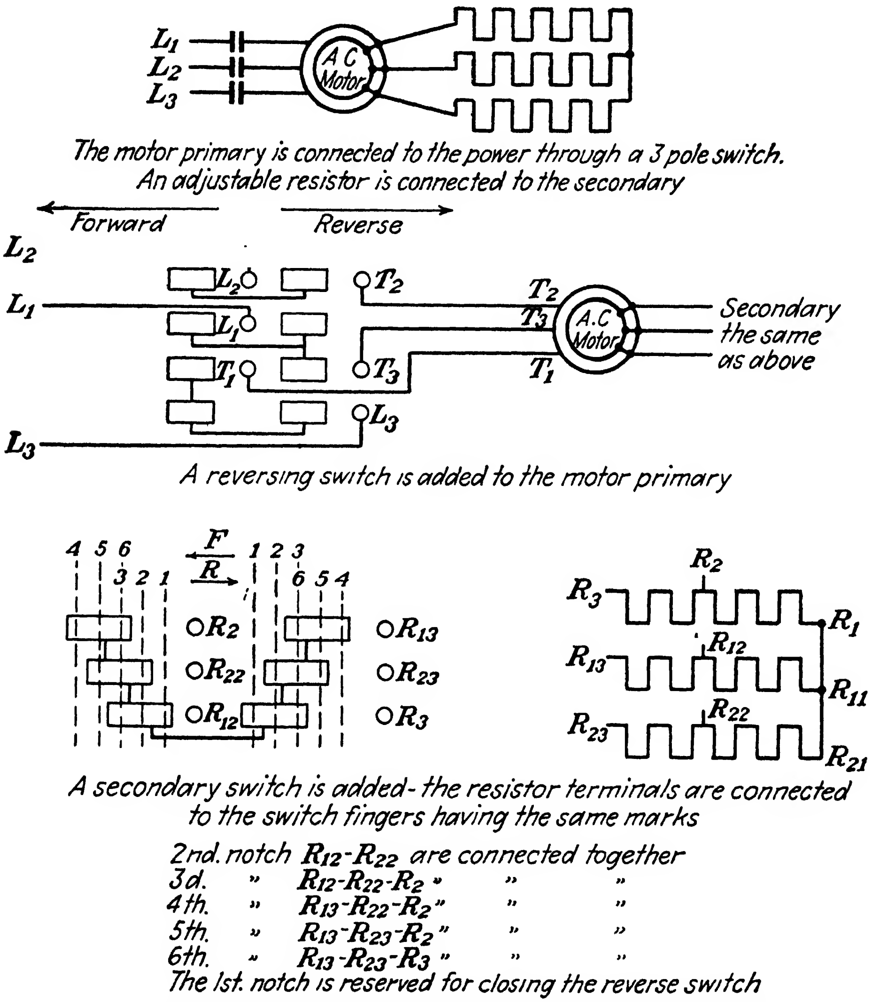


FIG. 24.—Steps in the development of the diagram shown in Fig. 25.

Relays—Overload—OL. Low Voltage—LV. Brake relay—BR. Field relay—FR. Transfer relay—TR. Accel. relay—Symbol from Fig. 26 followed by the number of contactor by which it is operated. Direct trip attachment—DTA. Other relays and control contacts on motor-operated cam controllers, 31 up.

Other Apparatus—Circuit breaker—CB. Master switch—MS. Limit Switch (spell out). Interlock—Symbol from Fig. 26 followed by number of contactor or letter

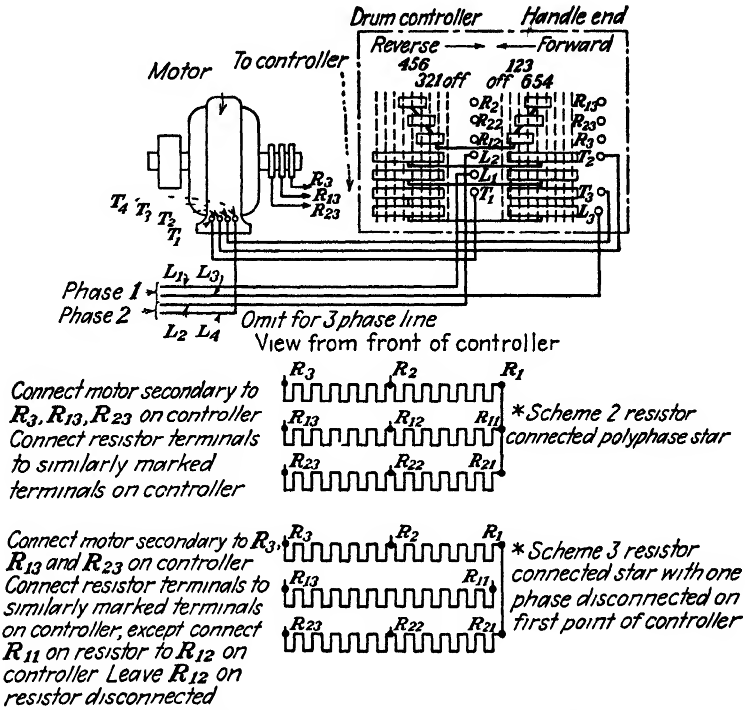


FIG 25 —Diagram of a reversing drum controller for a three-phase, wound-secondary, induction motor

Part	Direct current	Alternating current
Line	L_1-L_2	L_1-L_2-L_3, etc
Brush on commutator	A_1-A_2	A_1-A_2-A_3, etc
Stator		T_1-T_2-T_3, etc
Series field	S_1-S_2	
Brush on slip ring (rotor)		M_1-M_2-M_3, etc.
Shunt field	F_1-F_2	F_1-F_2
Commutating field	C_1-C_2	
Braking resistance	B_1-B_2-B_3	B_1-B_2-B_3, etc.
Armature resistance	R_1-R_2-R_3	R_1-R_2-R_3, etc.
Shunt-field resistance	V_1-V_2-V_3	V_1-V_2-V_3, etc.
Transformer, high voltage		H_1-H_2-H_3, etc
Transformer, low voltage		X_1-X_2-X_3, etc
Two-phase line		Phase 1 Mark L_1-L_3 Phase 2 Mark L_2-L_4
Two-phase stator		Phase 1 Mark T_1-T_3 Phase 2 Mark T_2-T_4

of relay by which it is operated. Knife switch—Symbol from Fig. 26 followed by the number and by Sw.

When more than one panel appears on the same diagram, add a dash and the panel number after the regular marking of relays, contacts, interlocks, etc.

FIG. 26.—Symbols used in controller diagrams shown in this book.

Instrument transformers should be marked Current Transformer or Potential Transformer. Transformers supplying control circuits should be marked Control Circuit Transformer.

Terminals.—The terminal markings shown on page 29 are used in this book.

The connection between the fused knife switch and fuse should not be marked. Terminals of meters should not be marked.

When two points with standard marking are connected to the same terminal (as S_2 and R_4) give both markings at the point where the con-

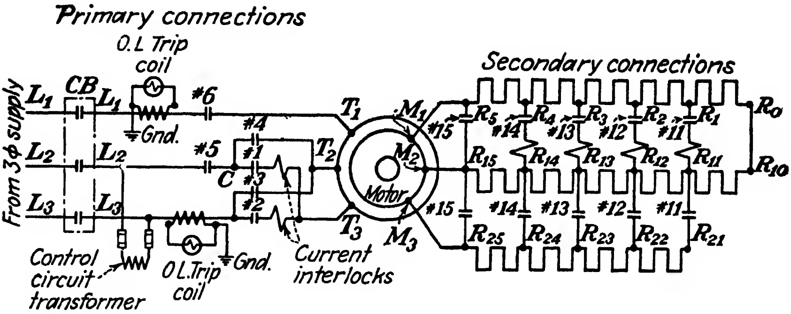


FIG. 27.—An elementary controller diagram.

nection is made. Letters *A*, *B*, *C*, *F*, *H*, *L*, *M*, *R*, *S*, *T*, *V*, *X* are not used for terminal markings other than those given above.

Mark pilot-motor terminals the same as for the main motor, but use small letters a_1-a_2, f_1-f_2, s_1-s_2.

When more than one motor or when motors and generators having the same marking are shown on one diagram, the regular marking must be preceded by a letter indicating the machine, to avoid confusion when making connections.

Examples: For generator, GA_1-GA_2, etc. For motor, MA_1-MA_2, etc. For exciter, EA_1-EA_2, etc.

Resistor marking on diagrams must agree with marking on the resistance drawing.

Additional Terminal Markings.—Shunt-brake coil, b_1-b_2. Control circuit, *x*-*y* (unless connected directly to terminals having different marking). Grounded terminal, G.

Control sequence table

Cont	Hoist 6	5	4	3	2	1	Off	Lower 1	2	3	4	5	6
1	O	O	O	O	O	O							
2								O	O	O	O	O	O
3	O	O	O	O	O	O							
4								O	O	O	O	O	O
5	O	O	O	O	O	O		O	O	O	O	O	O
6	O	O	O	O	O	O		O	O	O	O	O	O
11	O	O	O	O	O				O	O	O	O	O
12	O	O	O	O						O	O	O	O
13	O	O	O								O	O	O
14	O	O										O	O
15	O												O

FIG. 28.—A control sequence table.

Autotransformer terminals are marked 1, 2, 3, etc. To avoid errors in making connections the transformers should be marked Transformer *C*, Transformer *D*, and Transformer *E*. On the controller, the terminals to which transformer *C* is connected are usually marked 1*C*, 2*C*, etc., these terminals being connected to taps 1, 2, etc., on transformer *C*. The terminals to which transformers *D* and *E* are connected are usually

marked 1*D*, 2*D*, etc., and 1*E*, 2*E*, etc. For three phase, terminals marked 1 are usually connected together, either permanently or while starting.

In addition to using standard symbols and markings for apparatus and terminals, it is also desirable to mark the control lines so that they can easily be traced, especially on complete diagrams; otherwise, it is sometimes very difficult to trace the connections and to understand the operation of a complicated diagram. The most satisfactory and most easily understood method of designation is that of numbering the wires deci-

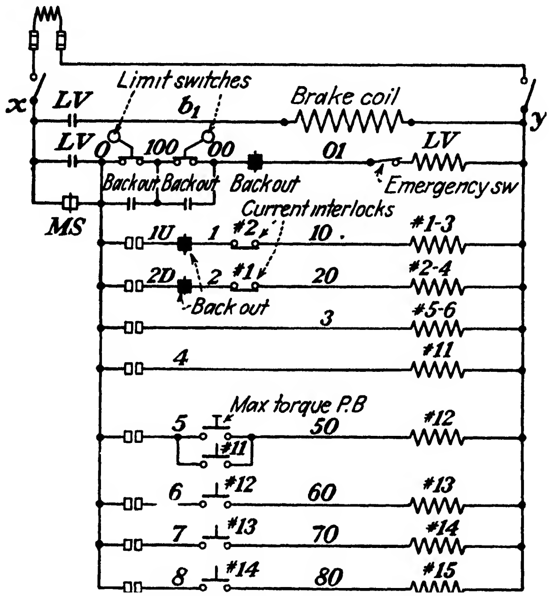


FIG. 29.—A control circuit line diagram.

mally, as is shown schematically in Fig. 31 and in actual diagram in Fig. 30. The energy supply lines for the control are marked + and − for direct current, and x and y for alternating current. Where the supply line goes through a relay or a limit switch before reaching the master controller, it is numbered 0. Where two or more of these are in series, they are considered as a unit and no markings are placed between them. When they are in parallel, or in series with taps taken off between them, these are numbered 0, 00, 100, 101, etc.

The fingers of the master switch, or the contacts of control push buttons, etc., and the lines leading therefrom are numbered 1, 2, 3, etc., odd numbers giving forward and even numbers giving negative rotation on a reversing controller. Each line is given the same number at both ends and, if it is long, at convenient intermediate points, to make it easier

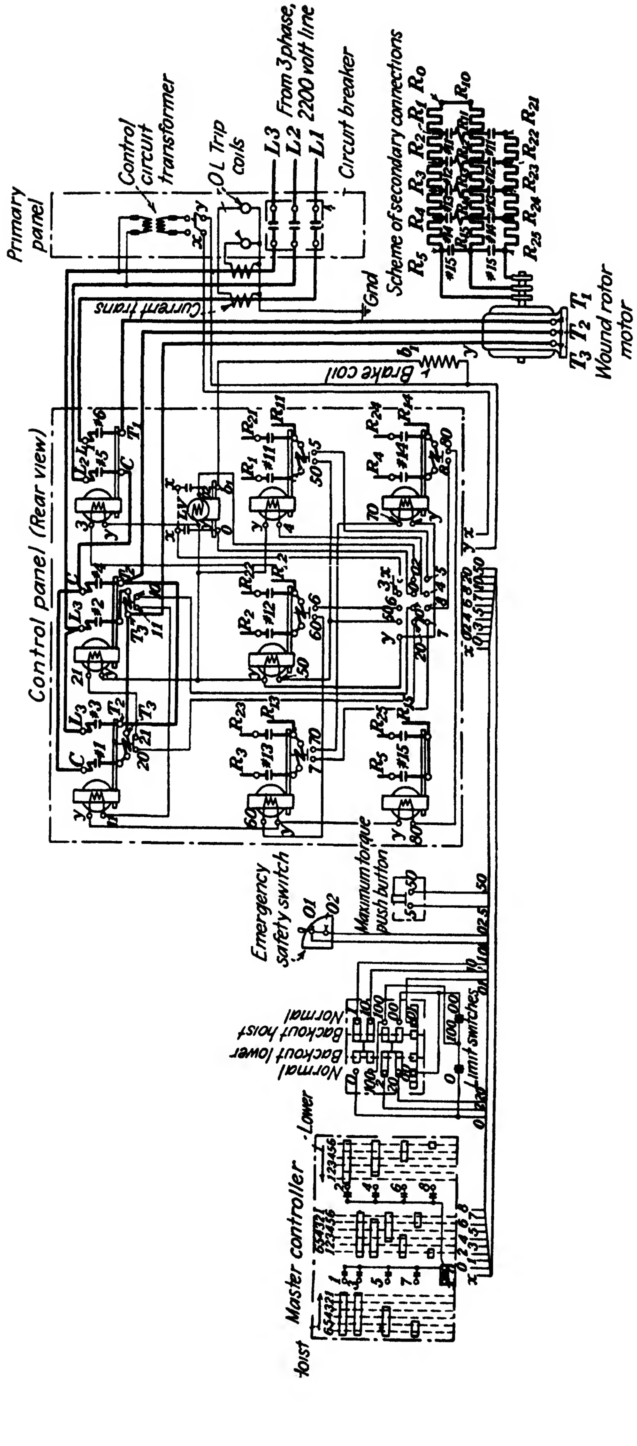


FIG. 30 —A complete controller wiring diagram.

to trace. When a circuit goes through a coil, an interlock, or other *equipment, the number is changed, being multiplied by 10 at the first* break and increased by one at each additional break, as is shown in Fig. 31, until it reaches the other terminal—or y. Where a line branches, the branches are numbered, when possible, in the order of normal operation. Where a line taps onto one previously numbered, it takes the number first assigned, as is shown in Fig. 31. By this system, any line with a number starting with 2—for example, 20, 21, or 24—originates

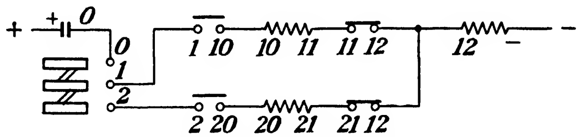


FIG. 31.—An elementary controller diagram showing how intermediate points of branch circuits are marked.

on master-controller finger 2. This is a great convenience in studying the diagram.

GENERAL SUGGESTIONS

Simplify the diagrams as much as possible; the lines should be at least ⅛ in. apart. Main-line connections should be shown by heavy lines and control-circuit connections by lighter lines. In no case should the lines be too fine to blueprint clearly. Double crossings of lines should be avoided and single crossings used as little as possible. Make the connections with few bends or offsets and, where possible, in straight lines. Make all lines in the diagram, except very short connections, either horizontal or vertical. Do not show connections running diagonally across the diagram. Shunt-field and shunt-braking connections should be shown by light lines; armature and dynamic braking connections, by heavy lines. These connections are mentioned merely as illustrations; the principles can be applied to all the other connections.

On controllers for large motors, all heavy-line connections are made by copper strap. The controller should be arranged so that these connections are as short and straight as can be and have as few crossovers as possible. These heavy connections add materially to the cost of the controller and it is desirable to spend ample time in arranging the controller so as to reduce the cost of these connections.

Controller diagrams usually show the rear view of the panel, as connections are usually made on that side of the panel, and the wireman who uses the diagram faces the rear of the panel. External wiring diagrams are made facing the front of the panel if the external connections are located on the front of the panel; otherwise, this diagram should be made as though the reader were facing the rear of the panel.

Each separate piece of apparatus should be enclosed in a rectangle made up of a broken line, as shown in Fig. 30. This indicates what part of the diagram applies to each piece of apparatus. It also shows where the wires pass from one piece of apparatus to another.

Small resistors mounted directly on the panel should be shown in their relative positions. This is particularly true of small resistor tubes connected in series with magnet coils.

The parts of a motor or a generator, such as the armature, field coils, and brake coils, should be shown grouped together. Where motors, generators, and exciters are coupled together, they should be so indicated on the diagram.

When a control-circuit switch is divided from the main-circuit knife switch, it should be connected outside the main knife switch, so that the control connections can be tested without starting the motor.

It is customary to group the control-circuit terminals close together, usually near the bottom of the panel. This is very convenient in making the connections to the master switches and other auxiliary apparatus. In the smaller controllers the main-line connections are often grouped together, at either the top or the bottom of the panel. For the larger controllers the lugs for external connections are located on different parts of the panel, in order to reduce the number of joints in the circuit.

When a knife switch and fuse are used, connect the switch to the line in such a way that the fuse will be dead when the switch is open. This is done by connecting the fuse to the hinge terminals of the switch and the line to the other terminals. Single-throw switches should open in the direction of gravity, to prevent the switch from accidentally closing. Do not place a knife switch above the main contactor, as the arc from the contactor may burn the operator's hand.

The connection of two or more controller coils in parallel causes sluggish opening of the contactors, owing to the discharge between the coils. This is particularly true in the case of large contactors or where coils of different sizes are in parallel. It is advisable to separate coil circuits in all cases.

If a resistor is connected in parallel with a coil, it gives slow opening of the contactor; the lower the resistance, the slower the action. If a resistor is connected in series with a coil, and the coil design is so modified that the resultant flux is the same as before, the speed of closing is increased; the greater the resistance, the greater the effect.

If a condenser is connected in parallel with a contactor coil, it may cause the contactor to open more quickly. If there is considerable residual magnetism, the condenser may increase the time of opening, rather than decrease it. A condenser should be used with considerable care where the time of opening is an important factor.

The two paragraphs above apply to d.c. control, as it is not good practice to use resistors or condensers in connection with a.c. control equipment. The use of a resistor or a condenser is ordinarily for the purpose of reducing the arcing on a control contact in series with d.c. coils. They may, however, be used to advantage in some cases in timing the operation, in order to obtain a desired sequence.

Where one side of a circuit is grounded, the master switch should be connected to the opposite side of the line. It is desirable to connect the master switch to the same side of the line as the motor armature of a d.c. motor, in order that the elementary diagram and the control-line diagram may show both the armature and the master switch on the left-hand side. When two or more panels are controlled from one master switch, special care must be taken to avoid "sneak" circuits. That is, after circuits have been established and checked to see that they will produce the desired operation, an extra check should be made to ensure that no additional, unintended operation is possible. Cam-type master switches have each contactor separately insulated. Where it is practicable, use a separate cam contactor for each control panel. Where a drum-type master switch is used, it may be necessary to provide separately insulated sections of the drum for each panel.

It is desirable to provide only one control knife switch and fuse for the entire equipment. Where the control circuit to each panel is not insulated through the master switch, all overload relays and the low-voltage protective relay should have their contacts connected in series.

Where a tryout switch is provided on the control panel, it should be electrically interlocked with the master switch in such a way that when the tryout switch is used the master switch will be inoperative.

The illustrations of diagrams shown in this article are intended to represent general methods of making diagrams. Other symbols and terminal markings may be found better adapted for various designs of apparatus.

CHAPTER IV

MAGNETIC CONTACTORS

The detail design of controllers should be left to the manufacturer who guarantees their operation and satisfactory service. The application engineer must select the proper type and size of controller for each particular drive and he is therefore interested in knowing how variation in design may affect the performance of a controller.

The capacity of a controller to carry current with a given rise in temperature may often be of much less importance than the durability of the contacts under repeated arc rupturing, and the design of bearings to withstand wear in dirty places. A knife switch will carry current but will not last long if it is used for rupturing current. Current-carrying ability may be impaired by long periods of operation without opening and closing and the consequent scouring action on the contact surfaces.

When the controller is used infrequently and for short intervals of time, a controller smaller than normal can be selected for the motor. An application of this kind would be a crane in a powerhouse used only for repair work. For frequent operation, such as occurs with motors driving reversing tables in steel mills, the controller should be more than usually liberal. The continuous-current capacity has little to do with either of these applications. If the motor drives a condenser pump in a powerhouse, continuous-current capacity is the most important consideration.

THE FUNCTIONS OF A CONTACTOR

The essential requirements of a contactor are current carrying and arc rupturing. Means for operating and closing the contacts, while necessary, are of secondary importance to these two principal functions. Whether the contact is operated by hand, by a magnet, or by an air cylinder, it is important that it carry the motor current without injury and that it be able to interrupt repeatedly any ordinary overloads that may occur. In addition, the mechanical parts must be rugged and able to stand the wear caused by repeated operation.

FACTORS OF CONTACT DESIGN

Current Carrying. 1. *Material for Manufacture.*—Hard-drawn or forged copper has given the best results.

2. *The Pressure between Contacts.*—Other things being equal, the heavier the pressure, the more current the contact will carry. There are, of course, limits to this pressure, but the carrying capacity can be materially enhanced with an increase of pressure.

3. *The Mass of the Contact.*—The greater the mass, the more heat is carried away from the contact surfaces and distributed through the adjacent material.

4. *Radiation.*—This factor determines the amount of energy that can be dissipated with a given temperature rise. With considerable mass

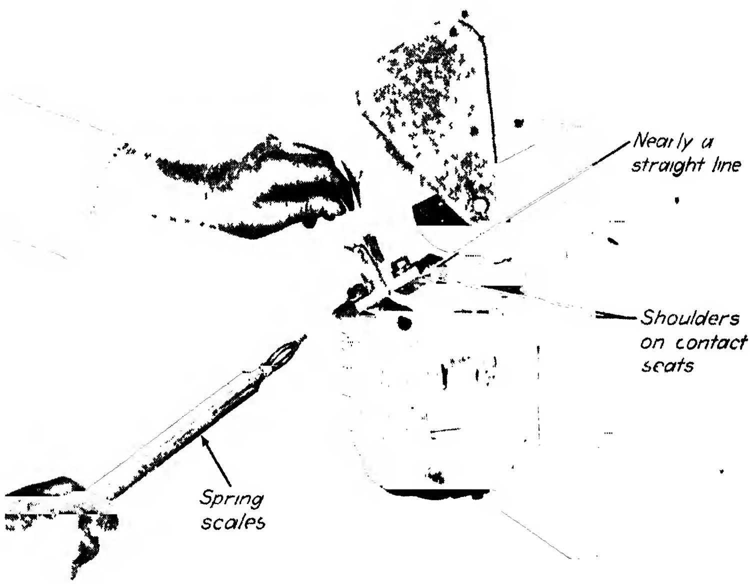


FIG. 32. - Method of testing contact pressure

in the contact, there is a greater radiating surface available for dissipating the heat.

5. *The Surface of the Contact.*—The surface should be clean and free from the oxide scale that forms when the arcing takes place in the air. This oxide is a nonconductor and interferes with the passage of current. Arcing under oil results in more or less of a carbon deposit, which is a conductor, although it may not be as good a conductor as the original material. Usually the design of the contactor will give a small amount of wiping action, which cleans the contact surfaces when the contacts are being closed. This sliding or wiping action wears away the contacts and should be limited to a very small motion.

Types of Contacts.—Contacts are usually of three general types:

1. *The Butt Contact.*—An example of this is the laminated copper brush used in large circuit breakers.

2. *Sliding Contact.*—An example of this is the drum controller that uses fingers sliding on a cylindrical surface.

3. *Rolling Contact.*—This form of contact is the more reliable and most satisfactory now in use. Contact is made at the tip and rolls down the surface to the heel (see Fig. 33).

Usually the movable contact member is attached to the armature of the magnet and mounted on an auxiliary pivoted member designated as the "contact support." The pivot of this contact support approaches the

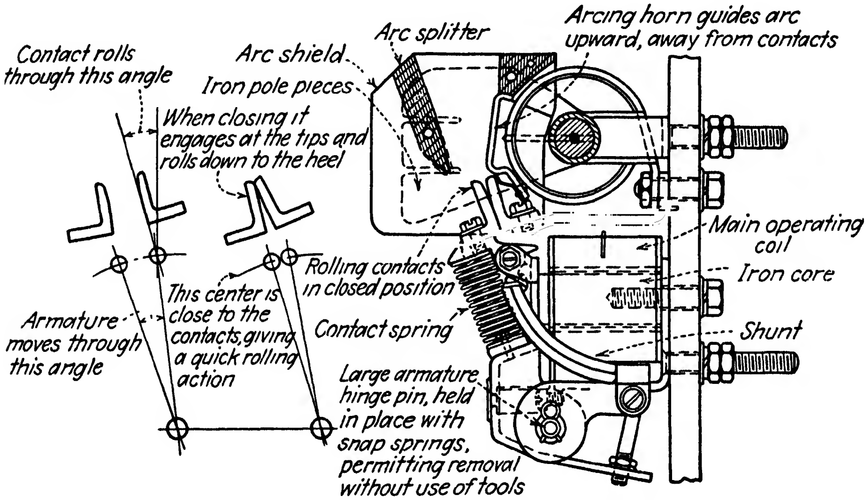


FIG. 33.—Action of rolling contacts.

stationary contact through the arc of a circle, and the movable contact is tilted forward so that its tip comes into contact with the stationary contact tip. The further movement of the magnet armature causes the movable contact to roll against the stationary contact until the heels or bottom parts of the contacts are in engagement. An important part of the design is the relation between the pin around which the contact support rotates and the position of the contacts. The action of the contacts against each other cannot be a true rolling action, as the contact-support hinge pin rotates through a circle and, owing to this rotating action, its center moves up and down. The rolling action, therefore, is combined with a small amount of sliding action. The least amount of sliding is obtained when the moving contact center is located so that it moves an equal distance on either side of the line drawn from the heel of the contact to the armature hinge pin. Even with this arrangement of centers, there

is always sufficient sliding action to keep the contact clean. Excessive sliding action causes additional mechanical wear on the contacts and in this way reduces their life. An endurance run on contactors having different amounts of sliding action makes the results of this wearing away of the contacts very evident.

Excessive sliding action is disadvantageous from another point of view, as well. If the surfaces of the contacts become rough, they have a tendency to lock together and prevent the sliding action. While this

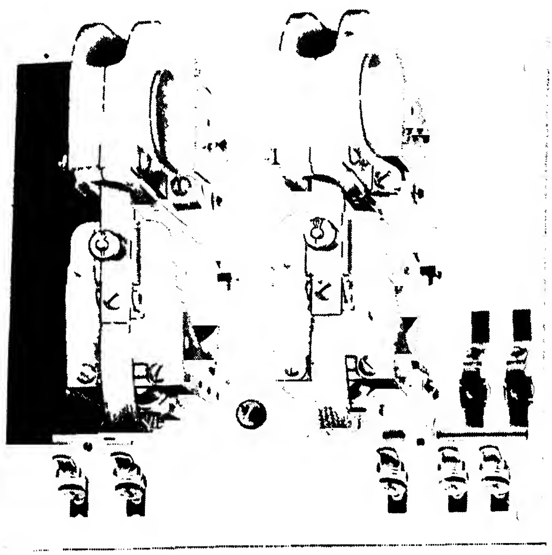


FIG. 34.—Two single-pole magnetic contactors manufactured by the Square D Company showing electrical interlocks and a mechanical interlock between the contactors which prevent both from closing at the same time. It is useful as a reversing switch.

locking together is not altogether positive, it has been found sufficient, in cases where the sliding action is excessive, to prevent the armature of the magnet from closing.

When a magnetic contactor is closed, the contacts strike together with considerable force and there is a slight rebound. When the contact rebounds, it draws a small arc, which softens the surface of the contacts at the point where they touched. If these contacts are permitted to come together at the same point after the rebound, there will be a tendency for them to weld or freeze, owing to the softened metal parts coming into contact. This reestablishment of contact at the same point is prevented by the closing movement of the magnet armature. During the period of rebound the armature has traveled closer to the magnet

core, and the center carrying the contact support is in a new position, so that contact is reestablished at another place.

The closer the center of the contact support is to the contact, the greater is the lever action exerted by the closing means and, therefore, the greater is the ease with which a welded contact may be broken apart. This is of particular value in connection with manually actuated contactors, as these are more likely to be welded, owing to improper operation. If the contact is closed by a cam or a lever, the operator can exert a very powerful force to break open any ordinary weld.

The Advantages of the Rolling Contact.—The advantages of the rolling contact can be summarized as follows:

1. The current is carried at the heel of the contactor. This is kept clean by a slight sliding motion during the closing period. The contact at this point is under the maximum spring pressure.
2. The arcing takes place at the tip of the contact, as this is the last part of the contact to separate.
3. The rolling action minimizes the bounce upon closing.
4. When the contacts are properly operated, they will not weld.
5. The absence of any considerable sliding action prevents the contact from sticking if the surfaces become roughened.
6. Heavier pressures can be maintained between the contact surfaces than where sliding contacts are used. The pressure is limited to about 10 lb. per lin. in. for sliding contacts, on account of the cutting action.

Use of Oil-immersed Contacts.—Oil-immersed contacts do not last nearly so long as do air-break contacts for the same service. This shortening of contact life is due to the intensely hot arc's vaporizing some of the oil, which burns the contacts and prolongs the arcing time.

Controllers for 2,200-volt and higher voltage service often have oil-immersed contacts, because these are very compact and cost less (see Fig. 253). One purpose in using oil-immersed contacts is to protect them from corrosive atmosphere or inflammable dust and entirely to enclose the live parts in order to shield persons from contact with live parts or the flash of the arc. Manual starters for squirrel-cage motors are usually enclosed and have oil-immersed contacts (see Fig. 259). This makes a universal-purpose starter for general application.

When a.c. magnets are used to close contacts, it is necessary to put a short-circuited turn, called a "shading coil," around part of the pole face, to cause a lag in the magnetic flux in the shaded portion. This eliminates "chatter" at the pole face when the magnetism in the core passes through zero. When the armature is in the open position and the coil is energized, there is a heavy rush of current, known as the "closing current." When the armature is closed against the magnet core, the current is about 10 per cent of the initial value. This is called the "holding current." The closing current is due to the increased

ampere turns required to give the reactive voltage necessary for balancing the line volts. The resistance drop is small and nearly 90 deg. out of phase with the reactive volts. Large a.c. contactors now use d.c. coils receiving power from a small rectifier, usually of the copper oxide type. This reduces the amperes required for the control circuit and eliminates all magnet noise.

Factors of Contact Design as to Arc Rupturing.—The design of contacts to rupture current depends upon the following items:

1. The shape of the contacts.
2. The size of the contacts.
3. The material from which the contacts are made.
4. The separation of the contacts when opening.
5. The speed of opening.
6. The strength and distribution of the magnetic blowout field.
7. The design and size of the arc box and the arcing horns.
8. The material from which the arc box is made.

All these items have their effect on the maximum rupturing capacity of the contacts and the durability of the contacts and the arc box under severe service. The greater the energy handled, the larger must be the arc-rupturing means and the more important it is to consider these various items in detail. The design engineer has at his disposal a certain amount of exact information, which is supplemented by experience and test data.

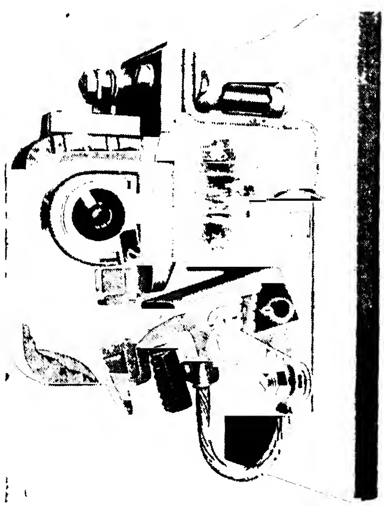


Fig. 35.—A Westinghouse single-pole magnetic contactor for d.c. power. See Fig. 36 for method of arc rupturing.

A general understanding of what takes place when an arc is ruptured can be obtained from a brief description of the action in the arc box.

The arc may be considered as consisting of a stream of positively and negatively charged gaseous particles or ions that travel rapidly from one contact to the other. This stream of rapidly moving ions constitutes the arc current between the contacts. Since it is a flexible conductor, it can easily be stretched out lengthwise or readily deflected. If a transverse magnetic field is applied to this conductor, the reaction between the conductor and the field will be similar to the action that takes place in a motor where a conductor carrying current is placed in a magnetic field. The arc conductor moves in the same direction as it would in a motor.

This movement increases its length, which cools the arc gases and increases the resistance to the flow of current. The increased length makes it more and more difficult for the voltage across the arc to maintain the flow of ions, until finally the arc is ruptured. The length of the arc depends upon the amount of current flowing when the arc is established, upon the voltage between the contacts, and upon the stored energy in the circuit. The length of this arc may readily be influenced by the design of the arc box and the blowout field.

In addition to the ions that make up the flexible conductor, some stray ions accumulate in the arc box. If the distance between the contacts is small, the voltage between the contacts may cause these stray ions to reestablish the arc by forming a new flexible conductor. Oscillograph records show that sometimes the arc is reestablished two or three times before it is finally interrupted in arc boxes not suitable for the service. The reestablishment of the arc depends upon the design of the

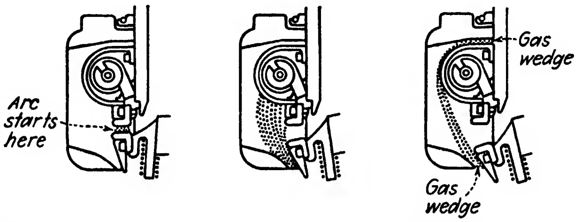


FIG. 36.—Method of arc rupturing used in contactor shown Fig. 35. The arc is moved from the contacts to the arc horn and shield around the blowout coil by the magnetic field which stretches and cools the arc.

arc box and the separation of the contacts. The higher the voltage, the greater is the separation required. If two contactors are used in series, there is much less liability of the arc's reestablishing itself. The two breaks in series also assist in rupturing the arc, as they require the maintenance in series of two flexible conductors made up of ions. They also distribute the heating effect between two or more arc boxes.

To rupture an arc, it is necessary to lengthen the arc path so as to increase the resistance and, therefore, to decrease the current, and, at the same time, to deionize the gas and to cool the arc. The contacts should also be separated far enough to prevent a reestablishment of the arc, or two or more breaks should be used in series for this same purpose.

OPERATION OF DIFFERENT TYPES

Westinghouse Magnetic Blowout.—An arc starts as the contact is broken (see Fig. 36). As the gap widens between the contacts, the arc is forced from the contact tips by the magnetic blowout. When the contacts are fully open, the arc has been stretched and the gas wedges keep the ends moving by the resistance of the gas in the pockets. This

prevents the formation of craters. The stretching and cooling deionize the arc and extinguish it. The magnetic blowout causes the arc conductor to move outward in the same way that a conductor on a motor armature is moved in its magnetic field. As the arc is forced outward, its ends travel along the arcing horns; this lengthens the arc and increases its resistance. The arc-box sides and the air cool this stretched-out arc and extinguish it.

Electric Controller and Manufacturing Company Magnetic Contactor. In Fig. 38 is shown the magnetic blowout action in the contactor illustrated in Fig. 37. When the contacts open, the current enters at the

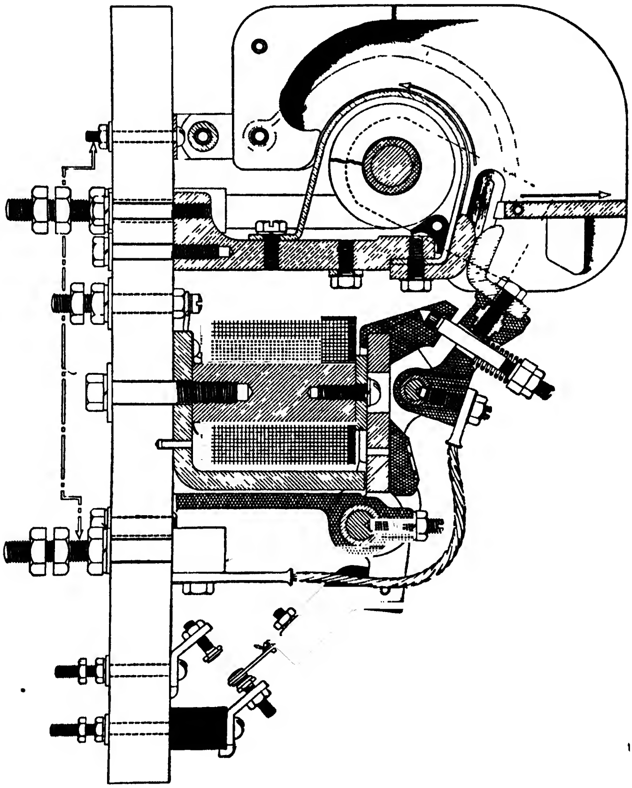


FIG. 37.—Single-pole d.c. magnetic contactor manufactured by the Electric Controller and Manufacturing Company. The action of the blowout field is shown in Fig. 38.

upper terminal to the blowout coil, and moves thence to the stationary contact, then to its arcing horn, and through the arc to the movable-contact arcing horn. Thence, by parallel conductors on the outside of the arc box, it passes to the lower terminal stud after the blowout field has transferred the arc from the moving contact to its arc horn. The current in the two parallel conductors outside the arc box is equal

to the arc current and moves in an opposite direction. The two circuits repel each other and force the movable arc into the center of its arc box.

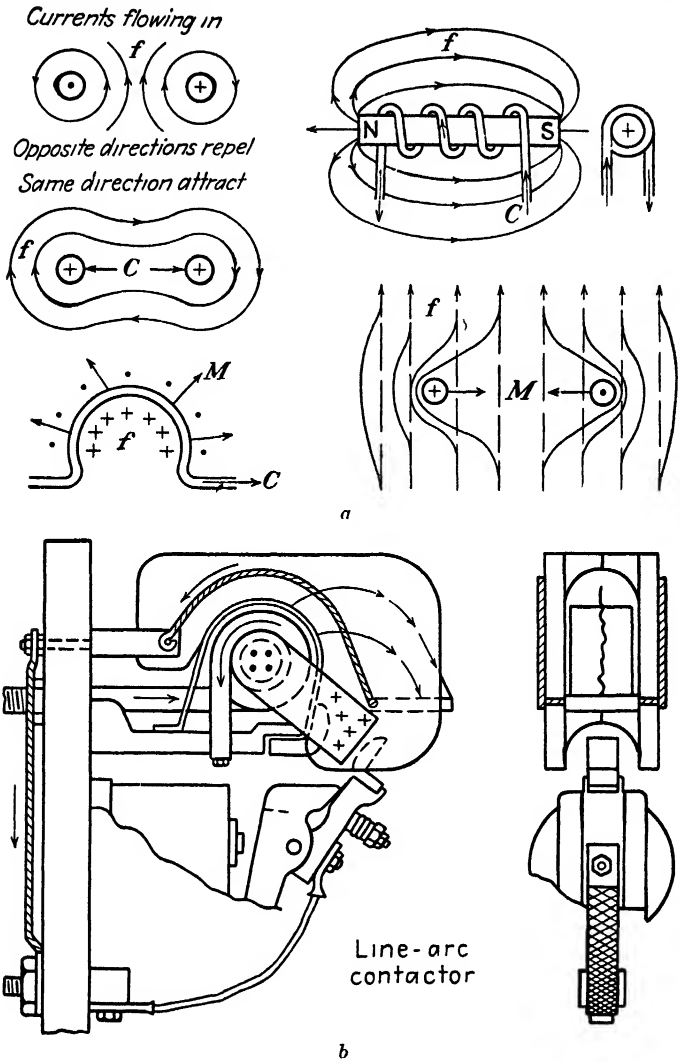


FIG. 38.—Action of the magnetic field in quenching the arc in contactor of FIG. 37. *a*, Method for keeping the arc in the center of the box by means of conductors parallel to the arc.

The Magnetic Blowout and the Arc Horns.—The cooling and deionizing of the arc vapor and the lengthening of the arc path are usually accomplished by means of a magnetic blowout. This lengthening and cooling process may be materially assisted by arc horns and by the proper shape of the arc box.

The ions, which maintain this arc stream, are not only cooled and discharged by contact with the sides of the arc box and the surrounding air, but are cooled also by traveling along the arc horns, which increase the length of the arc under the influence of the blowout field. The projection, or throw, of the arc beyond the edge of the arc box is, therefore, decreased and much greater energy can be broken in the same size of arc box. If the arc extends a considerable distance beyond the edge of the arc box, it ceases to be under the influence of the magnetic field and may continue to hang on for an appreciable length of time. The burning on the contacts and the arc box for any given current depends upon the length of time the arc is maintained. The further the arc must travel in order to be ruptured, the greater the time of burning. By the use of arc horns the arc is extinguished more quickly and, therefore, the amount of burning is decreased.

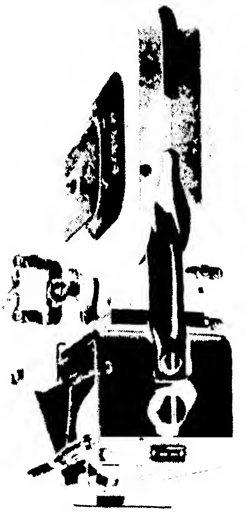


Fig. 39.—A General Electric single-pole d.c. magnetic contactor with blowout and electric interlocks. A sectional view is shown in Fig. 40.

DESIGN DETAILS

The arc can also be quenched by blowing it through a narrow slot in the arc box. This cools the arc and deionizes the gas, which reduces its volume. It has been found that a restricted-arc-box area at the arc terminals assists in rupturing it and also reduces the burning on the arc horns.

The General Electric Company was one of the first to use the narrow arc box opening (Fig. 39) for their magnetic contactors. At our request, E. H. Alexander has prepared the following explanation of the principles of the restricted-arc chute:

The restricted-arc chute is a mechanism often employed on magnetic contactors to facilitate the interruption of arc currents in air. The chute usually consists of some inorganic insulating material of the ceramic variety which has good ability to withstand heat shock and has a high resistance to the erosive effect of the arc. The material should also be a poor source of electron emission at any temperatures encountered under operating conditions within its rating. It does not follow that a material which has a high resistance to the erosive effect of the arc is necessarily the best chute material. Such an arc chute is shown in Fig. 39. The physical relationship of a restricted-arc chute to the other component part of a large d.c. contactor, is shown with one-half of the arc chute removed in Fig. 40.

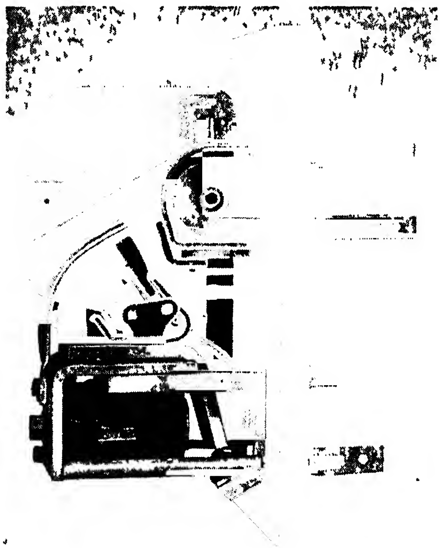


FIG. 40.—Sectional view of General Electric contactor shown in Fig. 39.

The principle involved is one of so directing the motion of the arc plasma that its shape presents a more favorable opportunity for heat transfer to the cooler side walls of the chute. As the name implies, the restricted-arc chute constricts the hot gases of the arc to a sheetlike formation; *i.e.*, the arc plasma has a high ratio of area to volume, thus presenting an optimum condition for heat transfer. Heat transfer occurs by conduction, convection, radiation, and even by the heat absorbed in vaporizing some of the arc-chute material. From the standpoint of conservation of energy, it is difficult to account for all the energy stored in the circuit being interrupted. There appears to be a considerable amount of difference between the heat appearing in the chute, contactor part, and the total heat represented by the system energy. Therefore, it appears that the action of the arc on the gases of the air may account for a considerable amount of energy absorption.

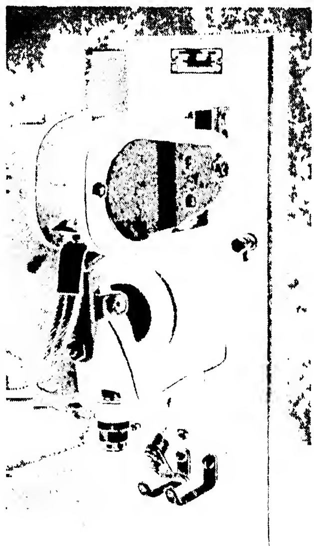


FIG 41.—Single-pole d.c. magnetic contactor manufactured by the Clark Controller Company.

The rapid introduction of impedance into the circuit being interrupted by the contactor depends in a large measure upon the speed with which the arc can be cooled to a temperature below which ionization of the gases

will not support current flow. In the design, a balance must be made between the velocity with which the arc is moved and the dimensions of the space. If it is blown too fast, the arc will reach the end of its travel on the arcing horns before the energy in the circuit is dissipated sufficiently so that the arc can go out. In this case there is excessive burning at the ends of the horns, both on the horns and on the chute. If the slot is too narrow, too high a velocity of arc travel may be reached, which may make the arc extend to dangerous distances beyond the chute on high overcurrent. Of course, arc length (stretching) and recovery voltage phenomena both take an important place in arc extinction. The "motor action" used to propel the arc through the chute is the result of the repulsion of two fluxes, the first flux being produced by the ampere turns of the blowout coil,

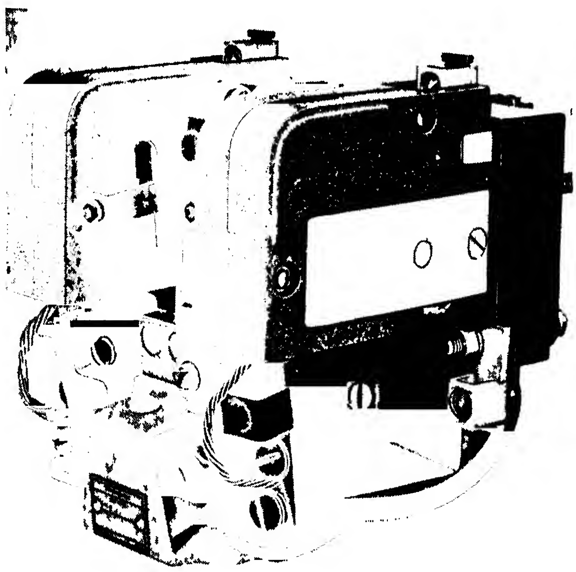


FIG. 42.—A Westinghouse two-pole d.c. contactor.

and the second flux resulting from the magnetic field surrounding the arc current itself. The proper distribution, polarity, and the strength of the blowout coil flux are factors which must all be balanced to produce a successful design.

The de-ion principle can be used to rupture an a.c. arc when the current passes through zero. The magnetic field moves the arc into a set of slotted metal grids (see Fig. 43), where the arc stream is deionized and does not reform after the current passes through zero. This principle is explained in several papers appearing in the *A.I.E.E. Journal*, February, 1929. A simple form of grid is used in commercial a.c. contactors where the arc-rupturing demand is limited. The more expensive rotatory-field method is required for circuit breakers of large rupturing capacity.

The De-ion Arc Quencher.—The de-ion arc quencher is used on a.c. power; it confines, divides, and extinguishes the arc quickly within itself without the usual flash and the attendant scattering of flame.

The successful operation of the de-ion contactor depends on the principle that the thin layer of air immediately adjacent to cold cathodes will withstand about 250 volts before breaking down, and, after having been subjected to an arc, deionizes rapidly and acquires the ability to withstand this voltage again very quickly. The arc space away from this thin layer of air does not deionize very rapidly. Consequently, in the De-ion contactor, a number of short arcs in series are utilized in order to get full benefit from the deionizing action of the cold cathodes.

As the arc is drawn between the contacts, it is forced upward by the magnetic field to the stationary end plates. After the arc transfers to the end plates it continues to move upward into the deionizing chamber, where it is extinguished almost instantaneously. The actual amount of time required for extinction of the arc depends upon the point on the current wave at which the circuit is interrupted. The arc is frequently extinguished before it has time to move above the slotted portion of the metal plates.

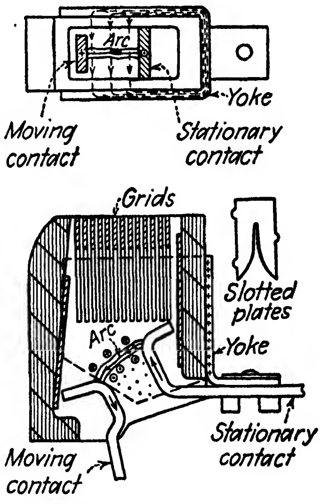


Fig. 43.— De-ion method for rupturing the a.c. arc.

As is illustrated in Fig. 43, these plates have a tapered slot. When a number of these plates are assembled as shown, they form a V-shaped groove into which the arc is forced. The contour of this groove is such that, as the arc moves upward, its cross section is decreased and the current density is increased with a corresponding increase in the arc voltage, *i.e.*, voltage drop across the arc. When a sufficiently high arc voltage is attained, the arc strikes to the metal plates, forming a series of short arcs, which may move up beyond the slotted portion of the plates. The arc continues until the current passes through the zero point of the cycle, at which time each layer of air between the plates is almost instantly deionized, and acquires the ability to withstand 250 volts much faster than any practical power circuit can supply this potential.

In testing a.c. contactors, a circuit in the neighborhood of 50 per cent power factor or less should be used, as this gives the most difficult conditions. It is much easier to rupture current on circuits of 100 per cent power factor, as the current passes through zero at the same time the

voltage is zero and the arc is not easily reestablished. On the other hand with a low power factor there is a considerable voltage between

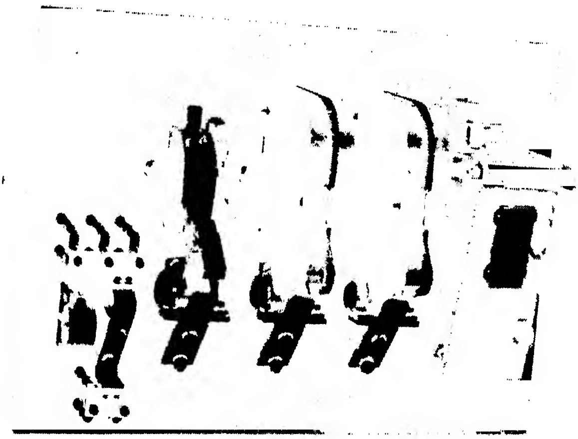


Fig. 44.—General Electric three-pole a.c. contactor with electrical interlock. One arc box has been removed to show the contacts and blowout coil.

Fig. 45.—Cutler-Hammer three-pole a.c. magnetic contactor and electrical interlocks.

the contacts at the instant the current passes through zero and, therefore, a reestablishment can take place more readily.

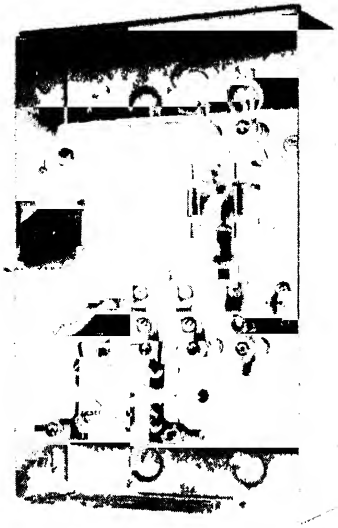


FIG 46 — Cutler-Hammer three pole a c contactor in cabinet One blowout has been removed to show the contact

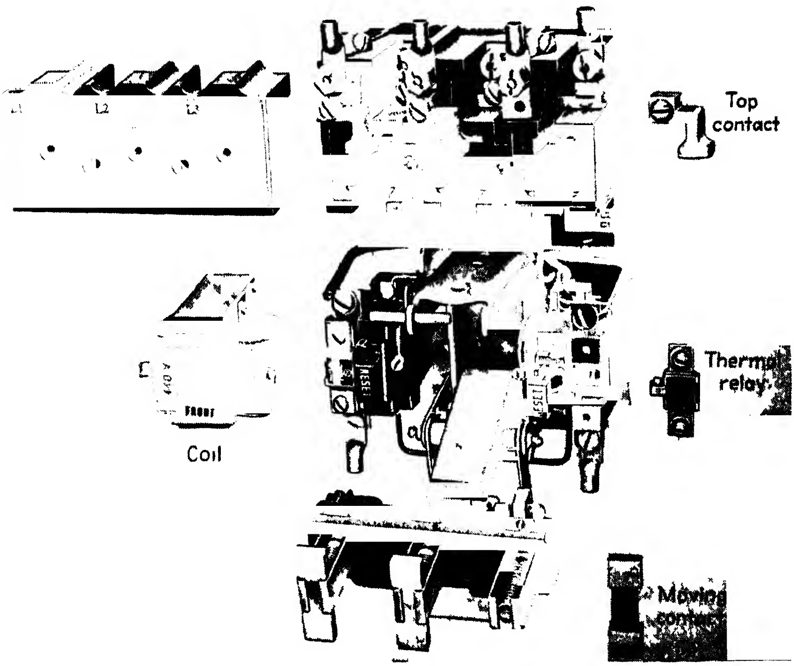


FIG 47 —Square D three-pole a c small size contactor Separated into part assemblies to show the construction

Where a large motor is started and stopped frequently, as in hoist service, it is preferable to use an air-break contactor. An oil-immersed contactor forms carbon in the oil each time the circuit is broken; an accumulation of this carbon will ultimately interfere with the proper operation of the contactor. Each time the arc is broken, the heat is transmitted to the oil, which in turn must radiate it from the outside of the case or tank. Repeated opening and closing will very materially increase the temperature of the oil, so that it is necessary to have a tank of proper proportions to absorb and radiate this energy without raising the oil to a dangerous temperature. These limitations have usually led engineers to prefer the air-break contactor for frequent operation.

RATING OF CONTACTS

The method of rating contacts depends entirely upon their service requirements. The two general methods followed are these:

1. Rating on a basis of a continuous ampere capacity.
2. Rating on a basis of durability.

Where the load on the contacts is continuous, the temperature rise under load conditions is an important item. In many cases, however, the wear on the contacts is severe and a much larger contact is used than would be necessary for continuous carrying capacity.

OPERATING COILS

The temperature of operating coils on magnetic contactors is affected by

1. Variation of line voltage, the magnetic air gap of an a.c. magnet, and variation in frequency on a.c. circuits.
2. Variation of the air temperature, ventilation, moisture in the air, etc.
3. Variations in the load on the current-carrying parts of the contactor. Heat is readily transmitted from one part of the contactor to another, so that local heating in some other part of the contactor may materially affect the temperature of the operating coil. Sometimes the use of a small lead wire to a contactor will make considerable difference in the temperature of the contacts and the operating coil.

The rating of contactors or other control apparatus is affected by an enclosing case or cover. Any restriction in ventilation increases the temperature and this is particularly true for control apparatus where the speed regulation of the motor is obtained through the use of resistors. Care should always be exercised in so locating heat-producing apparatus that proper ventilation will be obtained.

SHORT CIRCUITS

A severe short circuit can damage a magnetic contactor, as these contactors are not intended to replace circuit breakers; they are designed

to open any operating overload or stalled motor current; but they provide only limited short-circuit protection.

The drop in voltage resulting from the short circuit may cause the magnet to release its armature and open the contacts. This severe arc may damage the controller while the circuit is being opened by other means or the magnetic reaction of the severe current may force the contacts apart and cause them to chatter and burn. Fortunately, short circuits do not often injure controllers, because a severe short circuit

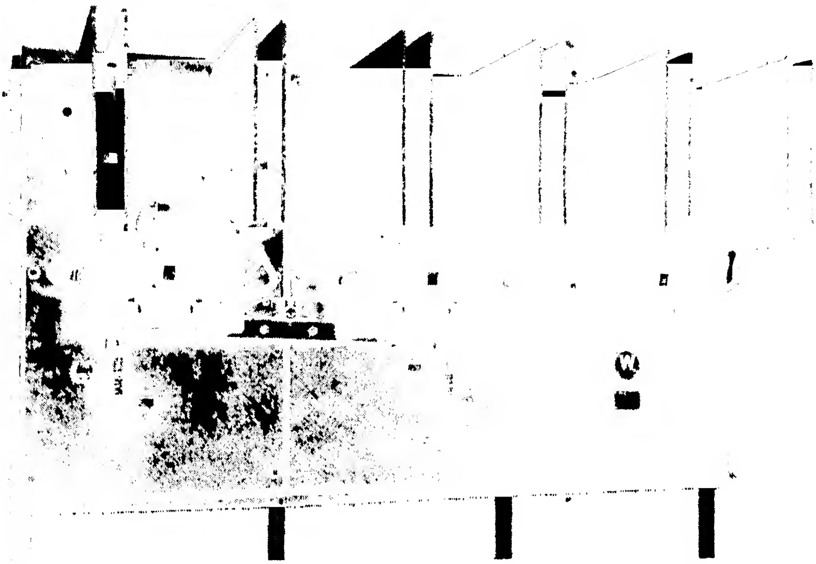


FIG 48.—Westinghouse 2,200-volt two-pole a c. contactors assembled in groups of three to control the primary of a reversing motor. Note the mechanical interlock between the two reversing contactors

seldom happens. The circuit impedance and the arc resistance limit the current so that the contactor can open the usual short circuit. When controllers are connected close to a heavy bus system, such as that of a large switchboard in a central station, the branch feeder to the controller should have special short-circuit protection. Fuses and a quick-acting circuit breaker are now available that can be used for this purpose. It is desirable to have this disconnecting means separate from the controller, so that the entire controller can be made dead when work is done on it. This is very necessary when the voltage is 2,200 volts or higher.

VOLTAGE REGULATION

A variation in line voltage beyond the guaranteed limits has a bad effect on control apparatus. A decrease in voltage may cause difficulty

in the closing of contactors or the operation of other magnetic devices. An increase in voltage will cause overheating in shunt coils. If a motor is operating at a given voltage and this voltage is suddenly decreased below the counter e.m.f. of the motor, the current through the motor will be reversed and generator action will take place. A small difference of voltage is sufficient to cause a heavy flow of current if the motor is connected directly to the line without external resistance. This not only causes a jolt to the motor and the controller, but it is very bad on the drive. If gearing is used, the back lash in the gearing may cause a serious blow to the teeth. Gears have been stripped in this way. If a chain drive is used, the results are even worse. Successful operation of electric drive depends upon a reasonably steady voltage; rapid fluctuations of the voltage are particularly harmful.

CHAPTER V

STARTING CHARACTERISTICS OF MOTORS WITH DIFFERENT METHODS OF CONTROL

The usual method of testing motors and controllers has been to use an ammeter and a voltmeter. These instruments gave good average readings, but owing to the inertia of their indicating member, only average values could be obtained. However, the improvement in the oscillograph and its general adaptation to commercial work has made possible the determination of many factors that are not shown by an ammeter. In some cases even the oscillograph has not been rapid enough to indicate excessive conditions of voltage and a spark gap has been used. Considerable practice is required to obtain good results with an oscillograph, and experience is required in reading these results. Investigations of this kind have proved valuable and in many cases mechanical analyses have been made, explaining in detail the phenomena observed with the oscillograph.

DIRECT-CURRENT MOTORS

The simplest form of motor and control, as well as the oldest, is the d.c. shunt motor with a controller that short-circuits the armature resistance during acceleration. When this combination was first used, care was necessary in accelerating the motor, to prevent excessive sparking or flashing. The starter was operated by hand and had a considerable number of steps. This was necessary in order to cut down the burning on the different steps and to introduce a time element, so that the operator, if he were careless, would not short-circuit the starting resistance too rapidly. Because of this practice, engineers have become accustomed to a considerable number of starting steps in accelerating these motors. They have based their calculations of the accelerating-current peaks on Ohm's law and have neglected a number of other factors that enter into this problem. The use of circuit breakers or overload relays without a time-element attachment has also tended toward the use of a considerable number of starting steps, in order to prevent their tripping on the overload peaks that occur.

The introduction of the magnetic contactor has provided a method of switching electric currents of considerable energy without the rapid destruction of the contact. The contactor can be used in connection with

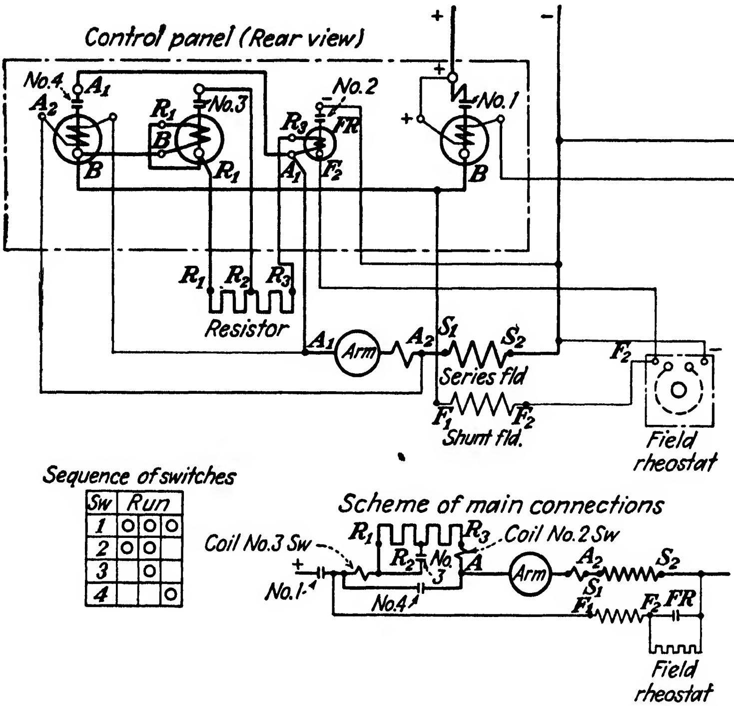


FIG. 49.—The connections of an automatic control used in tests to analyze the starting characteristics of motors.

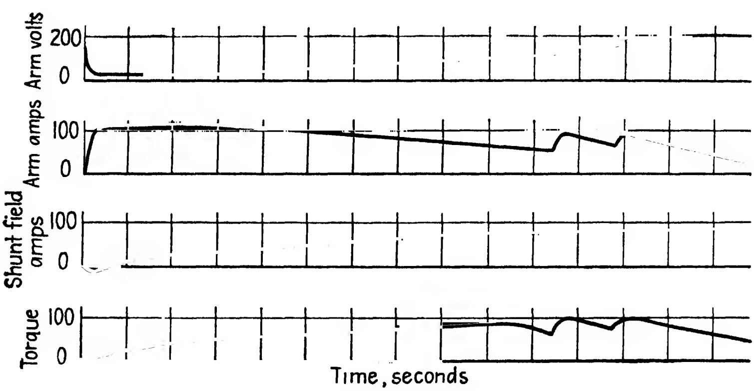


FIG. 50.—Starting tests of a 20-hp. 750-r.p.m. d.c. motor belted to a 50-kw. generator with no load on the generator. External resistance 1.35 ohms plus 0.25 ohm internal resistance in the motor windings. External resistance short-circuited in two steps at 120 and 160 volts counter e.m.f.

automatic devices for short-circuiting the resistance during acceleration, which eliminate the personal element and prevent careless manipulation. The use of contactors for automatic acceleration immediately reduced the number of starting steps, as compared with those of the manually operated starter. A feeling still exists that several steps are needed for starting even small motors. In order to obtain some actual information, a series of tests were made with an oscillograph on a d.c. motor accelerated automatically and belted to a generator of about double the motor size. A record was made of the armature current, the armature voltage, and the field current. In a few cases a Prony brake was used for loading the motor instead of its being belted to a generator.[1] The diagram of connections is given in Fig. 49. Figures 50 to 57 show results of some of the tests. The internal resistance given in the captions includes the complete resistance of the controller and the motor armature circuit, also the leads between the motor and the controller. It was measured from the + to the − terminals of the controller with the starting resistance short-circuited. In addition, as will occur in any installation, there was some resistance in the lead wires between the controller and the source of power.

The 50-kw. d.c. generator belted to the motor represents more inertia than usually occurs in practice. Figures 50 to 55 cover a period of about 2 sec. Figures 56 and 57 cover a period of about 4 sec.

Summary of Tests[2]

1. It seems unnecessary, with automatic acceleration, to use more than one intermediate step in short-circuiting the armature resistor used with small motors, except where special requirements are to be met. It is practicable to use one switch with motors as large as 15-hp. for general purposes and to operate this switch by counter e.m.f., setting the switch to close at 75 per cent of normal voltage.

2. If the motor field is zero or has a small value when the line switch is closed, the starting torque is also zero or has only a small value, and it will increase gradually so that the motor, or its load, will not be subjected to a heavy shock or jar when the lost motion in the drive is taken up.

3. The shunt field of small 2 to 1 adjustable-speed motors can be reduced in one step under normal load conditions without fear of undue torque or current. This practice can be safely followed with 50-hp. motors and perhaps larger. This covers the usual range of sizes for this type of motor. Most machine-tool motors are started light. Under this condition, the motor can be started successfully with minimum field strength and with the field relay omitted. This will enable the use of the same controller for constant-speed and adjustable-speed motors, supplying a separately mounted field rheostat for the latter.

4. Adjustable-speed motors can use one step of resistance for dynamic braking as the change in field strength tends to maintain the braking current constant over a considerable range of speed.

[1] The results of these tests appeared in the *Proc. A.I.E.E.*, February, 1917, p. 233.
[2] *Ibid.*

5. The time required to accelerate to 95 per cent of speed is very short. In these tests the time did not exceed 3 sec.

During the discussion of these tests, it was pointed out that the results obtained may have been materially affected by a drop in line voltage. It was admitted that some drop in line voltage would probably occur in most installations. The effect that the use of a small number of starting steps would have if the motor and the controller were located close to the powerhouse was, however, questioned. In order to determine this point, the writer had a number of tests made with the motor connected to the bus bars in the powerhouse. An oscillograph record was taken of the armature amperes, armature volts, and line voltage. The

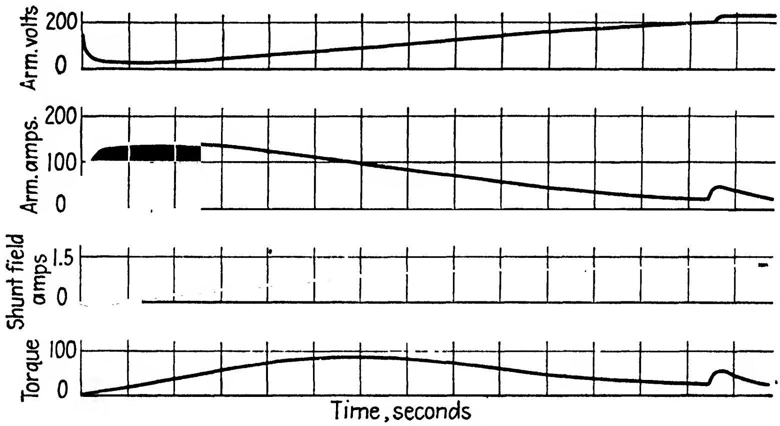


FIG. 51.—Starting tests the same as Fig. 50 except that the external resistance was short-circuited in one step at 190 volts counter e.m.f.

tests showed that there was practically no change in the line voltage during acceleration and that the current peaks obtained were about two-thirds of the value, as usually calculated, based upon Ohm's law. The results of these tests are shown in Figs. 58 and 59.

In calculating the starting resistance for a shunt motor, the steps are usually arranged in geometrical progression. This method is based on the assumption that each step of resistance is short-circuited when the motor current has reached a uniform minimum value. This value is that necessary to overcome the torque that the motor is required to develop during the accelerating period. During these tests, a standard 15-hp. 230-volt 825-r.p.m. shunt motor was accelerated under full load obtained by means of a Prony brake. The minimum accelerating current to overcome this torque was 50 amp. The line voltage was 258 volts and the resistance was short-circuited in one step. Following the usual method of calculation, and assuming two equal current peaks, a calculated external resistance of 0.905 ohm would be required in series with the

motor armature. This would give two equal peaks of 220 amp. each. The oscillograph record of this test, shown in Fig. 58, was obtained with 1.282 ohms in series with the armature and shows maximum current peaks of 168 amp. at start and 163 amp. when the resistance was short-circuited. This short circuit occurred when the counter e.m.f. across the motor brushes was 61.5 volts. This voltage divided by 0.268 ohm, which is the internal resistance, would give a peak of 230 amp. By extending the current peak to the instant when the resistance switch closed, the curve shown by dotted lines of Fig. 58 gives a close check upon the calculated value of the current. The effect of the armature self-induction is shown by the difference between the dotted line and the

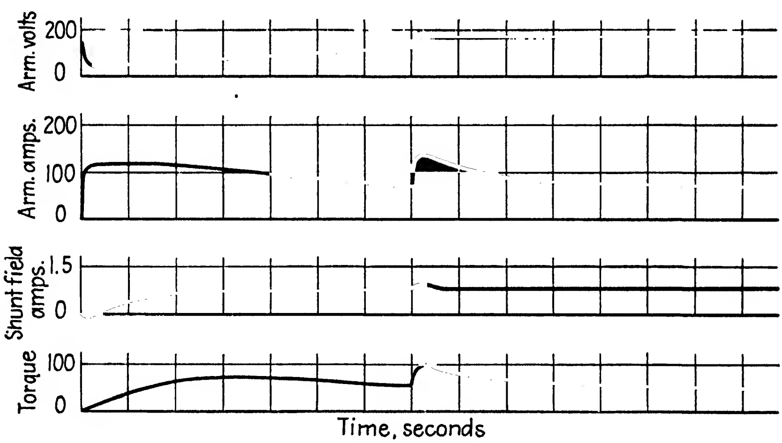


FIG. 52.—Starting tests of a 50-hp. 750-r.p.m. d.c. motor with a Prony brake load set for full load torque at full speed with 0.725 ohm external plus 0.25 ohm internal resistance. External resistance short-circuited in one step at 125 volts counter e.m.f.

heavy line. The starting peaks are thus shown to be about two-thirds of the calculated value, using the geometric progression method and neglecting armature reaction.

In Fig. 59 are shown the results of a similar test, accelerating with one-half full-load torque applied by Prony brake. The peak calculated in the usual way would require 138.6 amp., based on a minimum accelerating current of 20 amp. The actual peaks obtained were 110 and 102 amp., showing the calculated peak to be about 31 per cent in excess of the actual value.

The following mathematical analysis has been worked out for calculating the true current peak shown in Figs. 58 and 59.[1] By taking into account inductance and inertia, it is possible to calculate the true peak

[1] By A. A. Gazda, who made these tests.

current when a portion of the external series resistance is short-circuited. The differential equation for the transient current is

$$L\frac{di}{dt} + M\frac{di}{dt} + Ri + K_1\int i\,dt = E^{1}$$

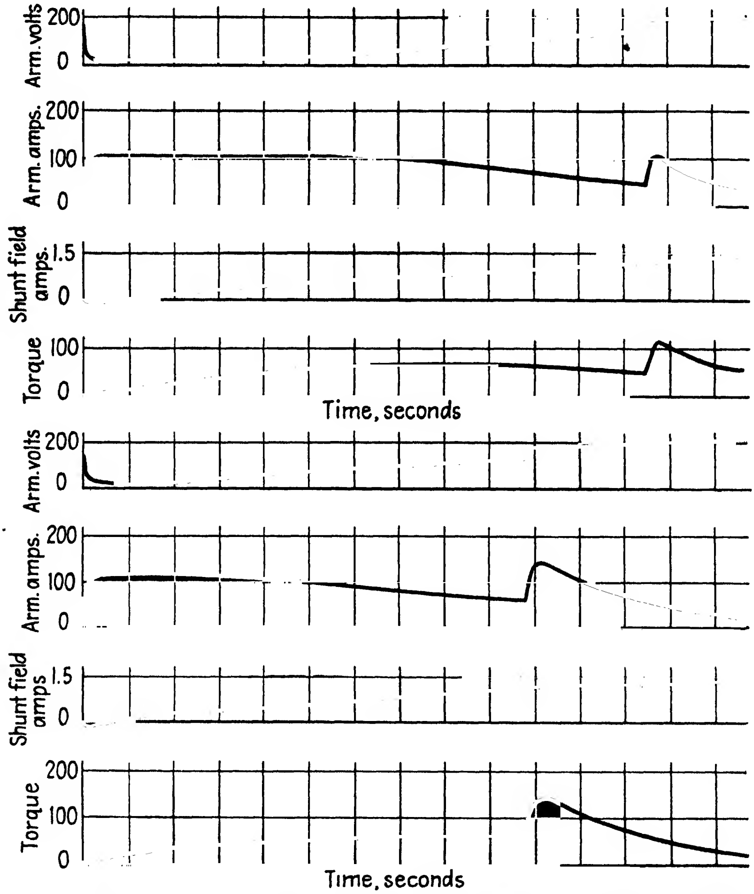


FIG. 53.—Starting tests of a 20-hp. 750-r.p.m. motor belted to a 50-kw. generator with no load on the generator. Resistance of 1.35 ohms for starting plus 0.25 ohm internal resistance. The starting resistance was short-circuited in one step at 150 volts counter e.m.f. for the upper set of curves and at 120 volts counter e.m.f. for the lower set. The adjustment for the upper curves gives equal current peaks and represents a practical controller.

The effect of mutual inductance M is very small and can be neglected. On the other hand, the counter torque T_c will be considered and assumed

[1] HANSEN, K. L., Starting Characteristics of Direct-current Motors, Eq. (22), *Proc. A.I.E.E.*, February, 1917, p. 272.

constant; hence,

$$L\frac{di}{dt} + Ri + K_1 \int i\,dt - K_2 \int T_c\,dt = E$$

Since we are considering the case in which the motor has come up to some percentage of full-load speed and a part of the series armature

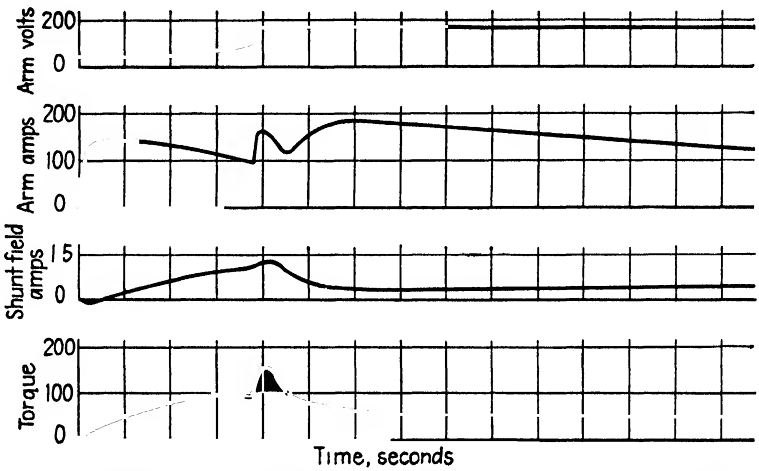


Fig. 54.—Starting tests of a 20-hp 500–1,500-r p m. motor belted to two 50-kw. generators connected to give 20-hp torque at 1,500 r p m Resistance 0 76 ohm starting plus 0 34 ohm internal resistance The starting resistance was short-circuited in one step when the counter e m f was 100 volts The field resistance was inserted when the starting resistance was short-circuited, the gradual rise of current being due to weakening the field

resistance is short-circuited, the initial counter voltage of the motor must be added to the left-hand side of the above equation, giving

$$E_1 + L\frac{di}{dt} + Ri + R_1 \int i\,dt - K_2 \int T_c\,dt = E$$

The general solution of this equation takes the form

$$i = A_1 + A_2 \epsilon^{\frac{-R+\sqrt{R^2-4LK_1}t}{2L}} + A_3 \epsilon^{\frac{-R-\sqrt{R^2-4LK_1}t}{2L}}$$

in which A_1, A_2 and A_3 are constants of integration. The value of these in terms of known quantities when the motor is accelerating under a constant resisting torque is

$$A_1 = I = \text{the initial current}$$

$$A_2 = \frac{I(R_s - R)}{\sqrt{R^2 - 4LK_1}} \qquad A_3 = \frac{I(R_s - R)}{\sqrt{R^2 - LK_1}}$$

where R_s = series resistance that is short-circuited
R = final resistance

When $4LK_1$ is greater than R^2, the current oscillates around the value required for the constant torque load, and the above general solution becomes

$$i = I + \frac{2I(R_s - R)}{\sqrt{4LK_1 - R^2}}\left(\sin \frac{\sqrt{4LK_1 - R^2}t}{2L}\right) \times \epsilon^{-\frac{Rt}{2L}}$$

The values of current represented by this equation were calculated for the period immediately following the closing of the accelerating switch, as shown in Figs. 58 and 59. These values check the oscillographic curve very closely and are shown in Table 1. This brings out the feasibility of calculating the actual peak current during the acceleration of the motor by means of series resistance

TABLE 1—ACCELERATING CURRENT VALUES

Time,[1] seconds	Amperes at half-load torque (Fig 58)	Amperes at full-load torque (Fig 59)
0 00	20	50
0 01	76	120
0 02	104 4	153 5
0 03	112 8	166
0 04	107 5	151
0 06	83 2	129
0 08	54 2	93
0 10	33 0	56 3
0 123	20	50
0 14	16 5	45 5
0 16	15 7	45
0 18	16 9	46
0 24	20	50

[1] Time is calculated from the instant that the resistance short-circuiting switch makes contact

These last tests confirm the writer's opinion that only a small number of starting steps are required in accelerating a modern d.c. shunt motor under ordinary conditions. Where a compound or a series motor is used, the starting torque will build up more rapidly, particularly with the series motor, so that this may prove a limiting condition during acceleration.

A number of tests were made upon a reversing planer equipment to obtain a detailed analysis of the different parts of the operation. These curves, one set of which is shown in Fig. 60, proved of considerable interest and value in designing these controllers.

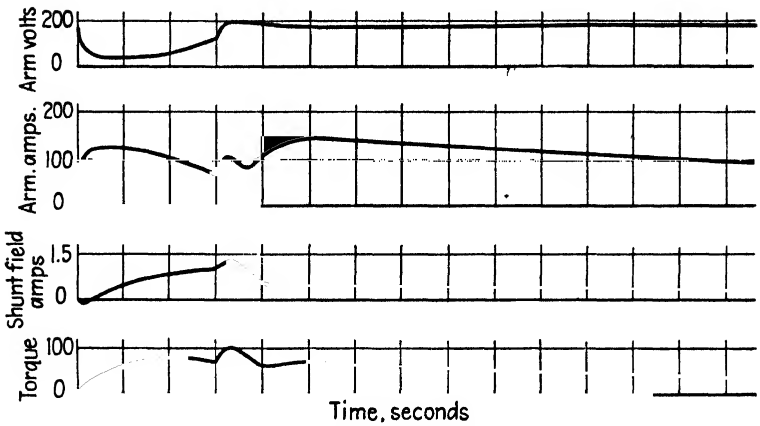


FIG. 55. Same data as Fig. 54, except that a Prony brake was used instead of the generator to give full load at 1,500 r.p.m. This gives a heavier starting torque and less inertia. The starting resistance was short-circuited at 120 volts counter e.m.f.

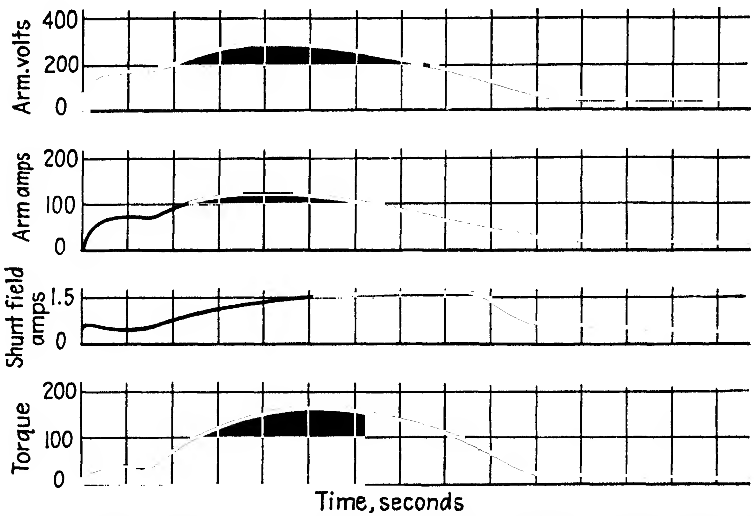


FIG. 56.—Effect of field variation on dynamic braking. Made with a 15-hp. 400/1,600-r.p.m. motor belted to a 50-kw. generator with no load on the generator. When the motor was operating at 1,600 r.p.m. the armature was disconnected from the line and connected to a resistance to give dynamic braking. At the same time the motor-field rheostat was short-circuited, strengthening the field to the 400-r.p.m. value. The curves show that the field built up faster than the speed decreased, so that the armature voltage at first increased and then remained practically constant for a considerable period. A strong dynamic brake was thus maintained until the motor speed was quite low, so that it could be easily stopped by friction or a mechanical brake.

ALTERNATING-CURRENT SQUIRREL-CAGE MOTORS

Under certain conditions, an excessive current may be obtained in starting a.c. squirrel-cage motors.[1] These conditions are not likely to

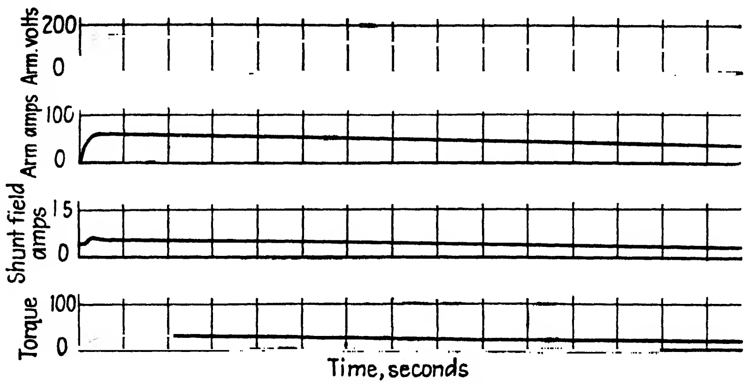


FIG. 57.—The same arrangement as Fig. 56 except that the motor field was not increased but remained at the 1,600-r.p.m. value, showing that a decreasing torque with decreasing speed will cause considerable drift before the motor comes to rest.

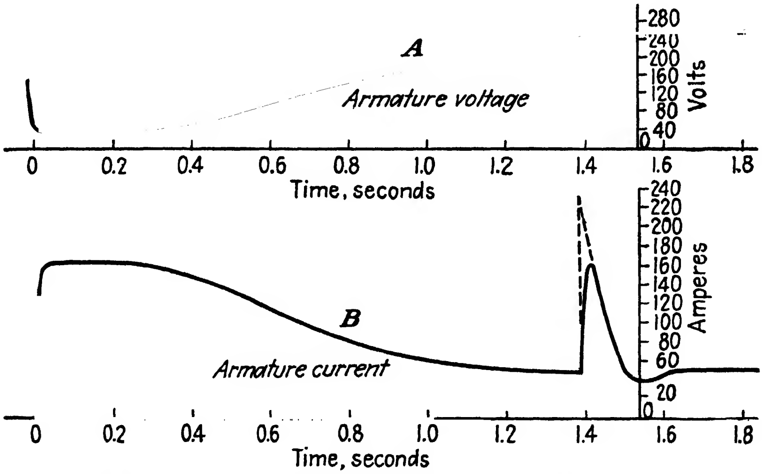


FIG. 58.—Starting tests of a 15-hp. 825-r.p.m. motor driving a Prony brake set for full-load torque. Starting resistance 1.282 ohms plus 0.268 ohm internal resistance. The starting resistance was short-circuited in one step when the counter e.m.f. was 161.5 volts.

occur in the smaller sized motors commonly used. The increasing use, however, of large-sized motors of this type, particularly with two and four poles, has made it necessary to consider these phenomena and has shown the importance of analyzing the motor and controller as a unit.

[1] HELLMUND, R. E., Transient Conditions in Asynchronous Induction Machines, *Proc. A.I.E.E.*, February, 1917, p. 205.

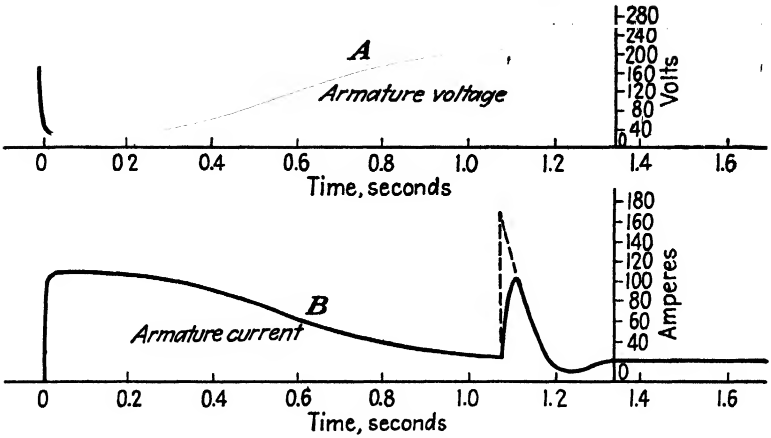


FIG. 59.—Same starting test as Fig. 58 except that the Prony brake was set for one-half full-load torque. The starting resistance was 2.062 plus an internal resistance of 0.268 ohm.

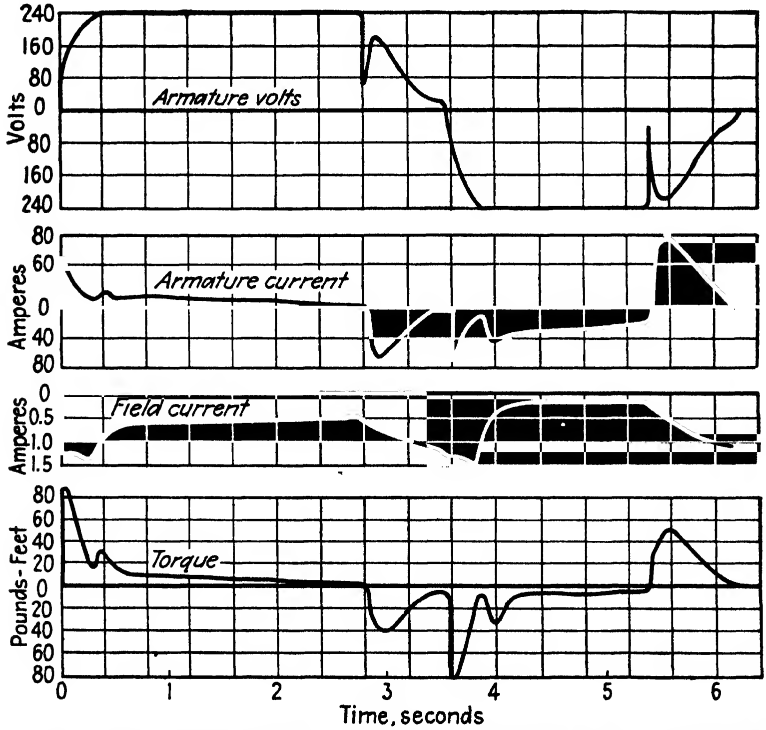


FIG. 60.—Starting tests of a 20-hp. 250/1,000-r.p.m., 230-volt shunt-motor operating a planer. Twenty-four-inch tool travel, 500-r.p.m. cut and 1,000-r.p.m. return stroke. Beginning at the left, the motor is accelerated for the cutting stroke, then dynamic braking occurs, followed by acceleration for the return stroke. The last loop is dynamic braking from the return stroke.

Several years ago, a series of breakdowns in the insulation of a wound secondary motor occurred, which were due to the inductive effect between the windings when the secondary circuit was opened before the primary winding was disconnected from the line. Oscillograph tests at first did not disclose this difficulty, but the use of the spark gap showed that approximately five times normal voltage might be obtained in the secondary circuit under these conditions. Prior to that time, it was the general belief that an a.c. motor had very little inductive effect of this kind.

FUTURE INVESTIGATIONS

The writer believes that there is an opportunity for considerable valuable work to be done along this line by universities and technical schools. Most of their laboratories are equipped with oscillographs and other means for this kind of investigation. The work is very interesting and instructive; in the foregoing description only the more important phenomena have been discussed. An analysis of the curves shows that the armature voltage is approximately equal to the line voltage at the instant of closing the circuit. The shunt-field amperage starts at zero and at first has a negative value, probably because of the reactive effect of the armature current. The peak values of the armature current show a round-off caused by the reactive effect of the circuit. This can be varied by changing the mechanical inertia of the parts or by changing the inductance of the complete circuit. The shunt field is assumed to follow the field current quite closely, although it undoubtedly does not reach the instantaneous values shown by the curve of field amperage. Further investigation in this line would be interesting.

CHAPTER VI

METHODS OF ACCELERATING MOTORS

In starting a motor from rest and bringing it up to full speed, resistance is inserted in the armature circuit of a d.c. motor, or the rotor circuit of an induction motor, to limit the current (see Chap. I). This resistance may be short-circuited gradually by a manually operated controller, or the resistance may be short-circuited in steps automatically as the speed of the motor increases. · There are several methods of short-circuiting this resistance automatically, as follows:

1. The counter e.m.f., or speed-limit, method.
2. The current-limit method—series relay—lock-out switch.
3. The time-limit method—dashpots, forced-acceleration—gearing—magnetic inductive delay.
4. Secondary frequency for induction motors.

More than one of these methods may be used in a single controller.

In considering methods of acceleration, the time required to close a magnetic contactor or relay should be considered. Relays are small and close quickly, but a large contactor will take several tenths of a second to close; when three or four accelerating contactors are used, they will introduce an appreciable time lag in a total accelerating time of 3 sec. When a section of starting resistance is short-circuited, the inductance of the armature circuit retards the increase of current while the motor is increasing its speed, so that the current peak is reduced.

Motors usually accelerate under a light load and the speeding up of the motor armature represents more than half of the work done. Fans, centrifugal pumps, and compressors do not pick up their load until nearly full speed is reached; the inertia of their rotating element is added to that of the motor armature. Machines usually have some friction load to be added. Slow-speed motors are easier to start than the high-speed ones. A centrifugal machine has a large inertia load because of its high speed and may require from 1 to 2 min. to accelerate. The time required to accelerate and the work done during this period influences the selection of the method used to obtain automatic starting.

This chapter explains the fundamental principles of the methods more commonly used for automatic acceleration of a motor. They apply to the d.c. motor, and most of them can be used with a.c. motors.

THE COUNTER E.M.F., OR SPEED-LIMIT, METHOD

This method has been applied to d.c. motors only, and is commonly used with shunt, or standard compound-wound, motors. When a motor is started from rest and accelerated to full speed, the voltage across the rotor terminals increases as the speed of the motor increases. If the coil of a magnetic contactor is connected across the motor brushes, the current in this coil will increase as the speed of the motor increases. By the adjustment of the air gap in the magnet, the contactor can be made to close at a fixed voltage across the motor brushes. The closing of the contactor can be made to short-circuit a section of the armature resistance. By the adjustments of several contactors to close at different armature voltages, the series steps of the starting resistance can be short-circuited and the motor be brought up to full speed.

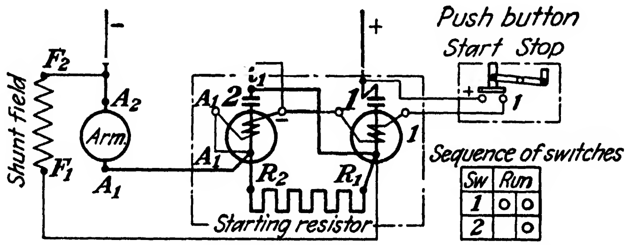


FIG. 61.—Connections for the counter e.m.f. method of accelerating a motor.

A simple diagram with one step of armature resistance and one magnetic contactor for short-circuiting this resistance is shown in Fig. 61. Several steps of starting resistance could, of course, be used with a contactor for short-circuiting each section.

The closing of switch 1, which is operated by a push button, connects the motor to the line in series with the starting resistor. One end of the operating coil of this switch is connected to the negative side of the line, and the other end is connected through the push button to the positive side of the line. The coil of switch 2 is connected across the brushes of the motor armature and will close the switch when the counter e.m.f. of the motor reaches a predetermined value. The closing of this short-circuits the starting resistor, R_1R_2, and places the motor directly across the line in the regular operating position.

With the elementary arrangement shown, if switch 1 is opened by pushing the stop button, switch 2 will not open immediately, as it will be held in by the counter e.m.f. of the motor. In most commercial switches a counter e.m.f. of 25 per cent of the full-speed value will hold the contactor closed. Under this condition, when the motor speed has been reduced to one-fourth full speed, and with contactor 2 still in the

closed position, the start button can be pushed, thus closing line switch 1, with the result that the motor will be connected directly across the line, without any starting resistance, and may cause a severe jar to the motor and the machinery that is driven by the motor. In order to avoid such a possibility, in commercial controllers an interlock is usually provided on switch 1, which opens the current of the coil on switch 2 whenever switch 1 is opened.

The advantages of this method of acceleration consist in its simplicity, since the switch does not need an auxiliary relay or any other accelerating devices.

Limitations arise where there is a considerable variation in the line voltage. An increase in line voltage will cause the contactor to close

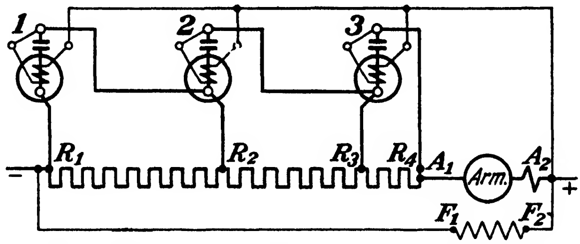


FIG. 62.—Connections, without the line switch, showing three contactors for accelerating the motor by using the counter e.m.f. method.

sooner than it should, and a drop in line voltage sometimes prevents the contactor from closing. These, however, are extreme cases. With a reasonable system of power distribution, especially if the power circuit is used for lights, the variation of voltage will be small and no trouble should be experienced. Another disadvantage may be caused by a change of adjustment, resulting from a change in temperature in the operating coil of the contactor. In a properly designed contactor, however, changes in the coil temperature will not cause trouble.

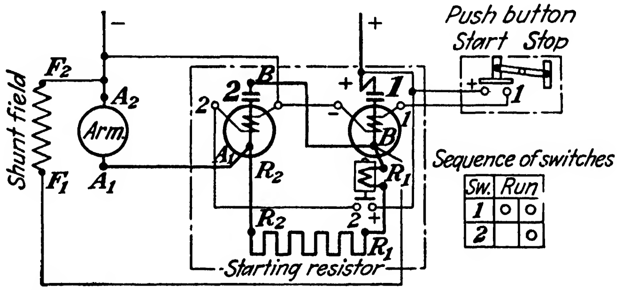
Where several contactors are to be installed, it is often necessary to furnish different coils, in order that adjustments can be made over the wide range of voltage necessary for the operation during acceleration. Interlocks are used for dropping out all but the last switch, in order to protect the low-voltage coils from overheating.

A modification of the connection shown in Fig. 61 is often used, in order to keep all the coils alike and to eliminate the interlock on the last switch. This arrangement is shown in Fig. 62. The operating coils of all contactors have one side connected to the motor brush farthest away from the starting resistor. The other sides of the operating coils are connected to the taps on the starting resistor, the coil on switch 1 being connected to R_2 on the resistor. The voltage on this coil is equal to the line voltage, less the drop in voltage through the first section of

the resistor, making a combined counter e.m.f. and current-limit method of acceleration. As the speed of the motor increases, the counter e.m.f. causes a decrease in the armature current. This reduces the drop through the first section of the starting resistance. The voltage on the operating coil of switch 1 is gradually increased until this switch closes. Switch 2 has its operating coil connected to R_3 on the starting resistor. The voltage on this coil is increased by the closure of switch 1. The increase in current, however, at this instant, causes a considerable drop in the second section of the starting resistance. As this current gradually decreases with the increased speed of the motor, switch 2 closes. The operating coil of switch 3 is connected across the motor armature, the switch closing when the counter e.m.f. of the motor is nearly equal to the line voltage.

THE SERIES RELAY, OR CURRENT-LIMIT, METHOD

There are a number of different schemes for using a series relay to control the acceleration of a motor. The principle involved in all these



Sw.	Run	
1	o	o
2		o

FIG. 63.—Simplified diagram of connections. A series relay used to regulate the acceleration of the motor.

schemes is a relay having a series winding that holds the relay contacts in the open position when the current exceeds a predetermined value. When the current is reduced sufficiently, the relay armature drops and completes the circuit to the shunt coil of a magnetic contactor. This method of acceleration can be used for either a.c. or d.c. motors. The arrangement most common in industrial applications consists of a series relay for each magnetic contactor. The relay contacts are held open mechanically until the electric circuit is closed with the maximum resistance in series. The relay armature is then released mechanically but will not drop until the current is reduced to the value for which the relay is set. The dropping of the armature completes the circuit for the operating coil of a magnetic contactor, which short-circuits a section of the starting resistance.

A simple form of this control is shown in Fig. 63. Switch 1 is controlled by a push button in the same way as in Fig. 61. This contactor is provided with a series relay mounted directly beneath the switch,

whose contacts are connected to the positive line and, through the operating coil of switch 2, to the negative line. When the relay armature is released, these contacts are connected together, thus causing switch 2 to close. When switch 1 is open, the contacts of the relay are held in the open position by a spring. When switch 1 closes, it releases this spring by mechanical means, so that the contacts may close. The current, however, in the series coil holds the armature in the upper, or open, position until the current has been reduced to a predetermined value. The armature then drops and its contacts are closed. This will not occur until after the motor has approached full speed, so that, when switch 2 closes and short-circuits the starting resistor, the increase in current will be limited. Several sections of armature resistance may be used with switches for short-circuiting each section, each switch being controlled by a series relay mounted on the preceding switch in the manner described.

The advantages of this method of acceleration are these:

1. The short-circuiting of the starting resistor depends directly upon the motor current.
2. This method is not affected by variation in line voltage, provided that there is sufficient voltage to close the magnetic contactors.
3. The adjustments for closing are not affected by the heating of the coil.
4. This method limits the load under which the motor will start. If the load is too great to allow the motor to accelerate sufficiently to reduce the current to the predetermined value, the relay will not drop and close its contacts, and therefore the starting resistance will not be short-circuited.

The limitations of this method are the following:

1. This method may result in too rapid an acceleration of the motor under light loads.
2. Additional apparatus is required, *viz.*, a relay for each resistance contactor.
3. The motor may fail to start under overload. This was given as an advantage, but in some cases it may be a disadvantage, depending upon the application.

Series Lock-out Contactors

The series lock-out contactor, when used for accelerating a motor, depends on the value of the armature current in the same way as the series relay method of acceleration. The contactor is designed so that it is held in the open position when the current through the operating coil or coils is in excess of a fixed value. When the current decreases to the value for which the contactor is set, it closes. There are two general types of these contactors, one using a single coil and the other a double coil. Some contactors depend for their operation on the saturation of the magnetic circuit, while others are designed for circuits not saturated.

The motor-armature current may pass through the operating coil, or the operating coil may be connected across a shunt in this circuit. A very convenient form of shunt is the starting resistor.

Single-coil Contactors with Saturated Iron Circuit.—This type of lock-out contactor is the one most easily understood. The following are several examples of this design.

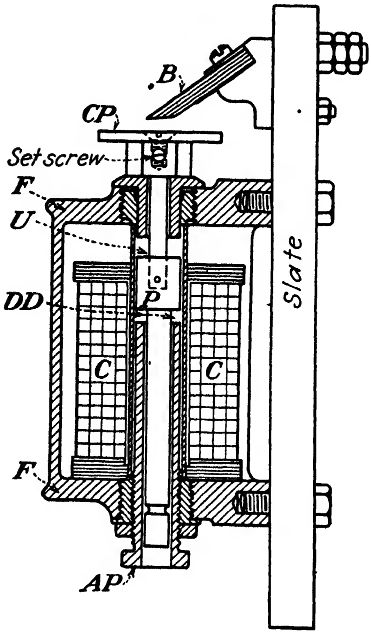


FIG. 64.—Lock-out contactor of the solenoid type with a series coil.

A lock-out contactor of the coil-and-plunger type is illustrated in Fig. 64. The operation of this contactor can be understood by referring to Figs. 65 and 66. The flux passing through the air gap U tends to lift the plunger P, which closes the contacts. This upward movement of plunger P is retarded by the magnetic flux in the air gap D. Part of the flux passing through P enters the narrow portion of the plunger and part passes through the air gap D. The iron in the lower portion of plunger P becomes saturated at high current values, forcing a part of the flux through the air gap D. As the current through the coil C decreases, the total magnetic flux is less. The larger part of this flux passes through the narrow portion of the plunger P, and less through the air gap D. When the current in the coil drops to the proper value, the flux through the air gap D is no longer able to prevent the upward movement of the plunger, which in turn closes the contacts.

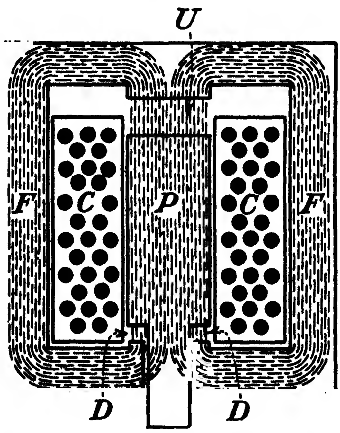


FIG. 65.—Section of lock-out contactor magnet, solenoid type, showing distribution of flux on overload.

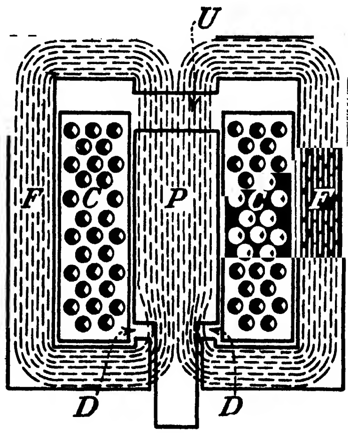


FIG. 66.—Section of lock-out contactor magnet, solenoid type, showing distribution of flux at time of closing.

The contactor shown in Fig. 64 has its air gap D located at the end of the sleeve near the bottom of the operating coil. This air gap can be adjusted up or down by means of the threaded hollow plug AP. The greater the air gap, the higher the current value at which the contacts are closed.

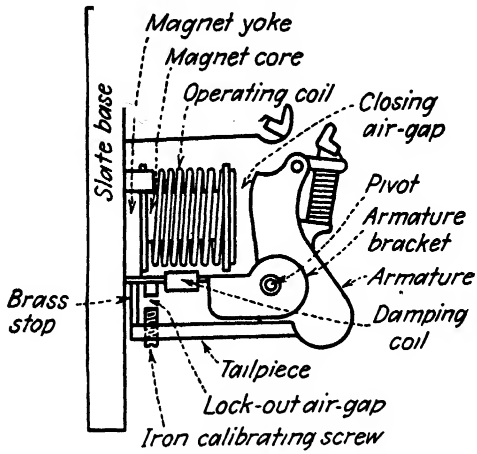


FIG. 67.—Clapper type of a series lock-out magnetic contactor.

A clapper type of lock-out contactor is shown in Fig. 67. The flux or magnetism in the iron is caused by current flowing through the operating coil. This flux passes through the air gap to the armature of the contactor. Part of this flux passes from the armature through the armature bracket to the magnet yoke, and thence to the magnet core. Another part of the flux passes from the armature through the tailpiece to the magnet yoke. The flux through the tailpiece exerts a pull, which prevents the contactor from closing. The magnetic path through the armature bracket has a small cross section, so that, when the current flowing through the operating coil exceeds a certain value, the bracket becomes saturated and the balance of the flux passes

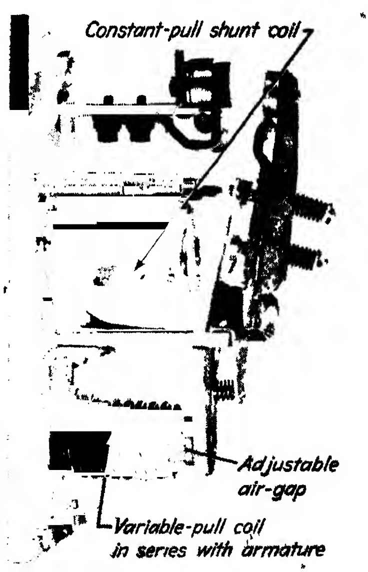
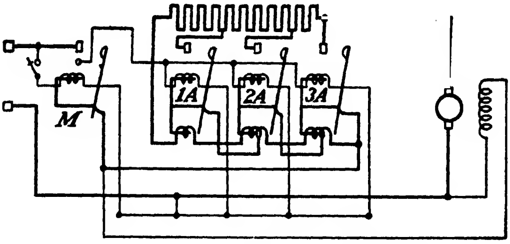
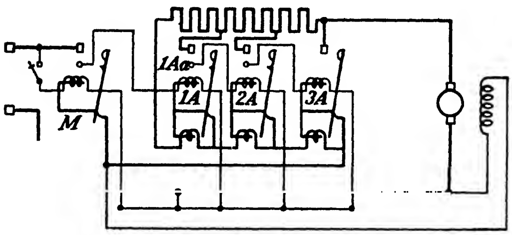


FIG. 68.—Two-coil magnetic contactor manufactured by the Monitor Controller Company. The closing coil is shunt wound and the lock-out coil on the bottom is series wound.



Circuit diagram of series interlocking
No coil interlocks necessary



Circuit diagram of shunt interlocking

FIG. 69.—The application of the contactors (Fig. 68) used for automatic acceleration. When M is closed the upper, or closing, coil of $1A$ is connected across the line and the lower, or lock-out, coil is in series with the motor. When the armature current decreases to a fixed value, the top coil closes $1A$ and its interlock $1Aa$ connects the top coil of $2A$ across the line. When the current drops, $2A$ closes and connects the top coil of $3A$ across the line. When the current is reduced to the fixed value, $3A$ closes. The starting resistor is now short-circuited.

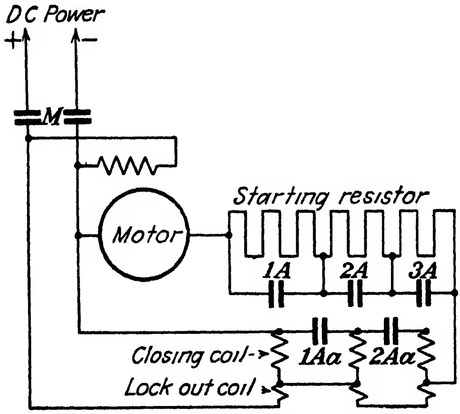


FIG. 70.—Contactor of Fig. 68, with a simplified arrangement of circuits. Control similar to Fig. 69.

through the tailpiece, holding the contactor open. As the current decreases, the flux in the saturated armature bracket remains constant, but the flux through the tailpiece decreases until it is not sufficient to hold the contactor open. The switch can be adjusted to close at a predetermined current value by changing the hold-out air gap between the tailpiece and the magnet yoke. This air gap is adjusted by means of a calibrating screw. The greater the air gap at this point, the higher is the current value at which the switch will close. When the circuit is first completed through the operating coil, there is danger of the switch's closing before the flux in the tailpiece is sufficient to lock it open. This tendency is overcome by placing a heavy copper damping coil around a portion of the armature bracket. When the operating coil is energized, this coil forces the flux to build up in the tailpiece in advance of the armature bracket.

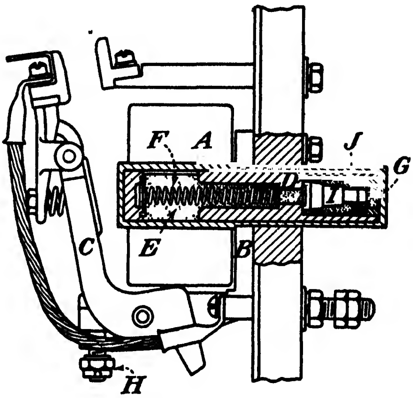


Fig. 71.—The Clark Controller Company's Vari-time magnetic contactor with a dashpot in the magnet core.

When the coil is energized, a flux is set up through the hollow brass cylinder *A*, steel frame *B*, and steel armature *C*; but since the brass core is nonmagnetic, insufficient flux is produced to cause the armature to close the main contacts. However, because of the well-known property of a solenoid to pull its core to its magnetic center a pull is exerted by the coil on the steel plunger *D*, tending to pull it forward into the center of the coil. This motion forward, however, is opposed by liquid *E*, trapped between the core and the front end of the hollow brass tube *A*. Hence, before the core can move forward to the center, this liquid has to pass through orifice *G* into the rear of the cylinder. This action controls the time required for the steel plunger *D* to move into the coil center and this provides a time delay for closing the contactor. The time can be varied by adjusting stud *H*. This contactor is used for accelerating motors.

THE TIME-LIMIT METHOD

The accelerating resistor is short-circuited under the control of a time-limit device. The contactors controlling the resistor may have the time delay incorporated as an integral part of them (see Figs. 71–73) or their magnetic circuit may be controlled by time-delay relays (see Figs. 75 and 77) or a master switch (see Fig. 78) may be used. Many different devices are used for this method of acceleration. Some of the more common time-delay methods are the following:

1. An oil or an air dashpot.
2. A magnetic or a mechanical drag instead of a dashpot.
3. A motor-operated timer.
4. A ratcheting device with reciprocal drive.
5. An escapement device controlled by a pendulum or a balance wheel, like a clock or a watch.

6. A magnetic inductive delay—usually the time required to collapse a magnetic field.

Dashpot devices are the oldest of these and are easy to understand, but experience and skill are required for designing them. The friction may vary as a result of dirt and temperature, and the viscosity of oil,

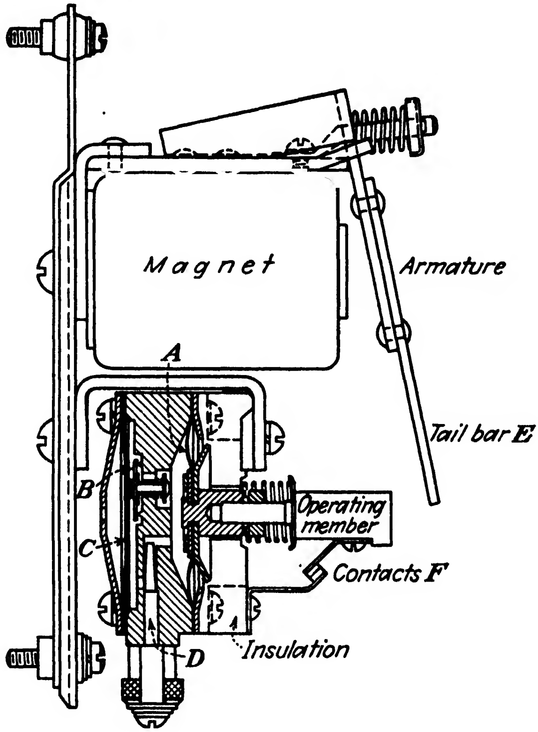


FIG. 72.—The Square D pneumatic time-delay unit consists of an operating member attached to a rubberized-fabric diaphragm *A*, which forces air from the upper to the lower chamber through check valve *B* when the magnet is energized. This flexes *C* downward to accommodate the air movement and opens the contacts. When the magnet is deenergized, the operating member moves to the right at a rate determined by the taper valve *D*, that regulates the flow of air from the lower to the upper chamber by screwing it in or out.

This device is used also to control the current for spot welding. It can be connected in the circuit in the same way as the magnetic lag relays in Fig. 84.

The tail bar can be mounted on the other end of the armature and the magnet reversed to set the time when the coil is dead and to release it when the magnet is energized.

if it is used, is affected by temperature. In some of the designs that are now used, these limitations are largely overcome. When a separate timing device is used for each step of resistance and fast acceleration is desired, accurate timing is not very important. Often the accelerating time must not be less than a fixed value, but may exceed it to take care of variation caused by temperature, etc. There must always be enough force to overcome the friction and the viscosity of the oil. The dashpots

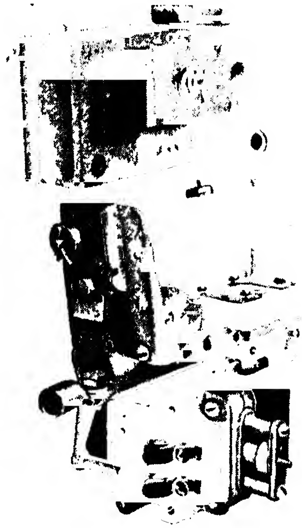


FIG. 73.—Square D magnetic contactor with the pneumatic timer shown in Fig. 72.

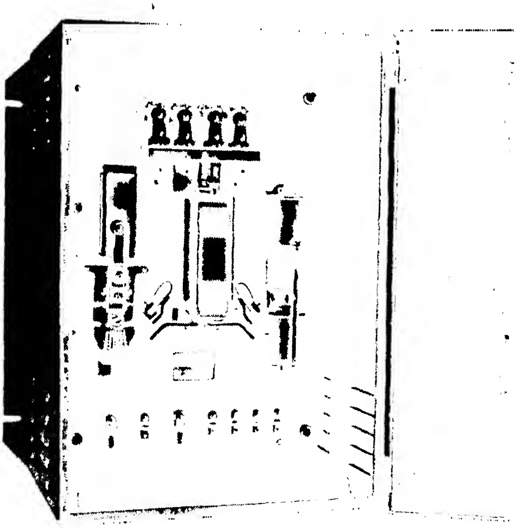


FIG. 74.—Monitor Controller Company's time-limit starter using a gear train for the time delay element. If the starter is for a d.c. motor, the line switch is the contactor on the left side of the panel. At the right of the panel is the overload relay. In the center is the accelerator, actuated by a solenoid magnet, that first closes the top contacts in succession to short circuit steps in the starting resistor. The bottom contact provides the final short circuit. The gear train provides a definite time for starting.

may require cleaning and adjustment from time to time. The application is usually made to controllers that require short periods of acceleration. Figure 71 shows a steel-mill contactor using an oil dashpot.

A magnetic drag is often a geared device coupled to a disk rotating through a magnetic field. A fan or a pump drag can be used in the same way. The actuating means may be a motor, a spring, or a weight. The device, which is usually applied in the form of a relay, is used where a long time delay is required

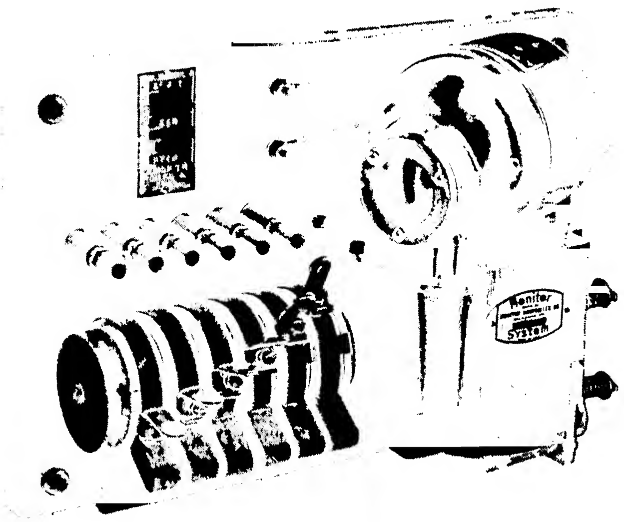


FIG. 75 —Monitor work-cycle timer mounted on a panel One unit may contain any desired number of contacts, this one has six

A motor operates a shaft, through gearing, that moves the rotating contacts into engagement with the stationary contacts The rotating contacts are connected to the shaft by friction members, which engage them when the magnet is energized After the moving contact engages its stationary contact, the friction member slips and permits the other contacts to be moved up The disconnecting of the magnet permits the rotating contacts to drop back to the starting position

The pilot motor-operated timer (see Figs. 75 to 79) usually depends upon its gear ratio for the timing. The coil of a series relay can be put into the main motor circuit and its contacts arranged to open the pilot-motor circuit and arrest its movement if a current limit is reached The pilot motor drives a drum shaft or a camshaft to establish contacts that short-circuit the accelerating resistor either directly or as a relay to close a magnetic contactor. Master switches often are of the drum type. When heavy currents are switched, the cam type is best.

These timers are well suited for long periods of acceleration. They are simple and rugged in design and are easy to understand A quick reset can be obtained by revolving the shaft one notch farther in the same

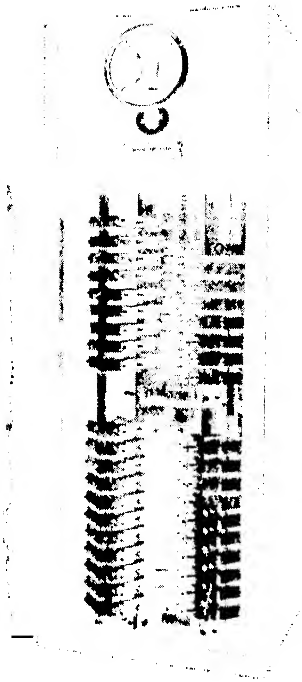


FIG 76.

FIG 77.

FIG 76 —Westinghouse cam controller for regulating the speed of a wound secondary-induction motor 12 to 20 steps 600 to 1000 amp The operating mechanism (see Fig. 77) is located in the top of the controller. The contactors and cams are shown in Fig 78

FIG 77 —Operating mechanism for controller shown in Fig. 76.

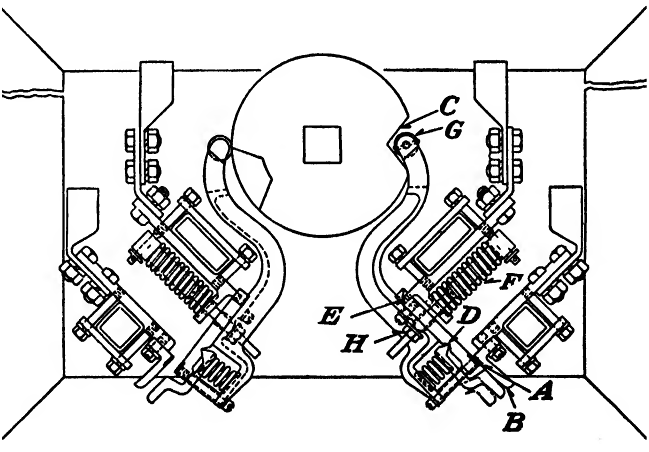


FIG. 78.—Contactors and cams for controller shown in Fig. 76.

direction of rotation to return to the starting position automatically when the line contactor is opened, or a magnetic reset can be used (see Fig. 75). This type of control can be used for both a.c. and d.c. motors.

FIG. 79—Westinghouse camshaft accelerator driven by a pilot motor on the back of the panel Handwheel for manual acceleration

The ratcheting and escapement devices fall into the same class They consist of gearing and an actuating means. The ratcheting device has a reciprocating drive actuating a pawl in a ratchet wheel. The escapement device is a simple and rugged set of gears similar to a clock or a watch movement, the timing controlled by a pendulum or by a balance wheel. These methods are applied to small starters and relays.

Accurate timing can be obtained with the pendulum arrangement for long periods of time. It closely resembles a motor-driven clock.

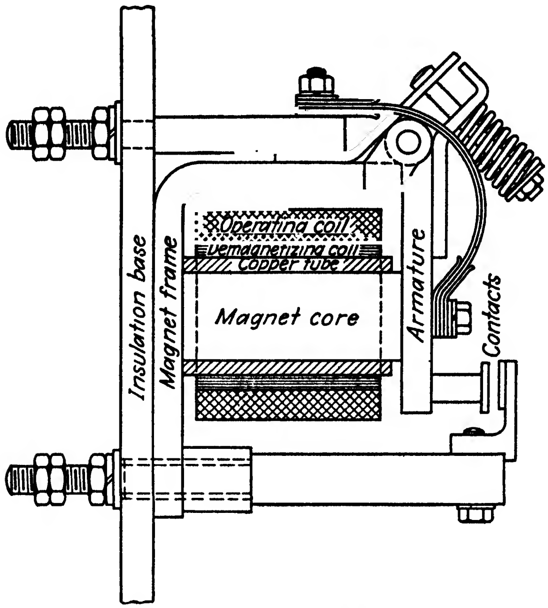


FIG. 80.—Elementary sketch of magnetic-timing relay showing the copper tube for increasing the time of armature release and demagnetizing coil to reduce the time. Either or both can be omitted. Time can be reduced by increasing the air gap.

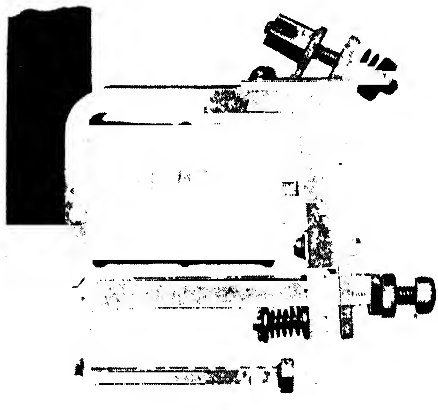


FIG. 81.—The General Electric Company's magnetic-time-delay relay.

The magnetic inductive delay has a variety of interesting possibilities. It is based upon the principle that time is required for magnetic flux in

an iron circuit to die out. The time can be lengthened by putting a copper tube around the magnet core. This becomes a short-circuited

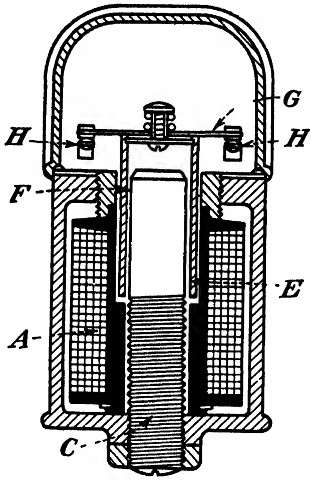


FIG. 82.—Electric Controller and Manufacturing Company time-current accelerating relay. *A*, series coil, *C*, adjusting core, *E*, aluminum tube, *F*, core, *G*, movable contact, *H*, stationary contacts.

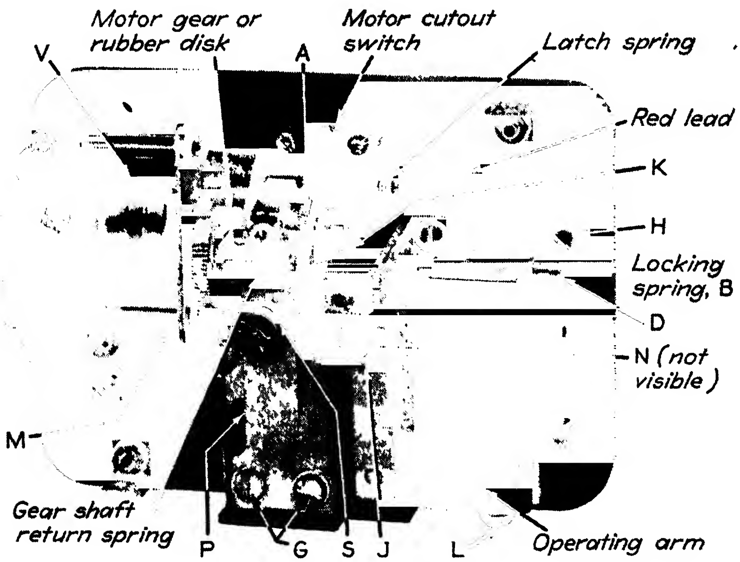


FIG. 83*a*.—General Electric Company's definite time-delay relay.

secondary and opposes any change of flux in the iron (see Fig. 80). The time can be adjusted by changing the thickness of this tube. Similar

results are obtained by short-circuiting the magnet coil. Resistance added to the coil circuit shortens the time. A second method is to change the air gap in the iron circuit. A small change has a large time effect.

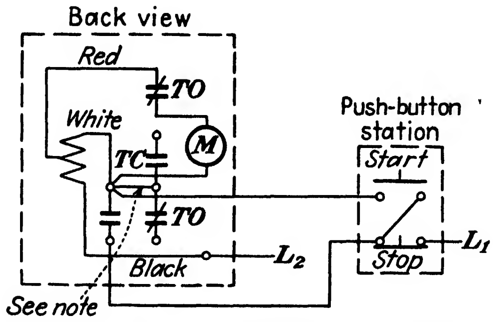


FIG. 83b.—Diagram for relay shown in Fig. 83a.

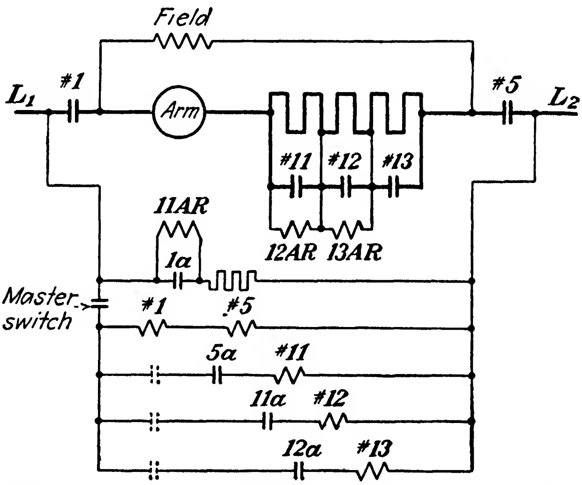


FIG. 84.—Magnetic time-delay acceleration. To start, close the master switch which closes 1, 1*a*, 5, 5*a*, and energizes coil 11. When the magnetism in 11*AR* is nearly zero, 11 and 11*a* close and short coil 12*AR*, which permits 12 and 12*a* to close and to short coil 13*AR*. This permits 13 to close. Magnets 11*AR*, 12*AR*, and 13*AR* can be attached to the tailpiece of a contactor (see Fig. 86) and 11*a* and 12*a* be interlock contacts or the magnets can be parts of separate relays (see Fig. 82) having contacts in series with coils 11, 12, and 13 shown in dotted lines. The collapse of flux in 11*AR*, 12*AR*, and 13*AR* can be controlled by the air gap or by damping means.

A third method is to use a small demagnetizing coil. A fourth method is to shunt the coil with a condenser or a resistor.

One type of relay has spring-closed contacts opened by a magnet (see Fig. 80). Upon starting, the magnet is energized to open the contacts, which are closed when the magnetic flux in the core decreases to the

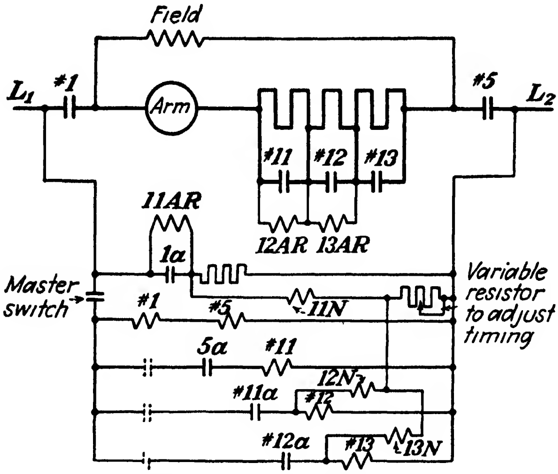


FIG. 85.—Magnetic time-delay acceleration with neutral-coil adjustment. Operation is the same as Fig 84 with neutralizing coils added to 11*AR*, 12*AR*, and 13*AR* to adjust the timing.

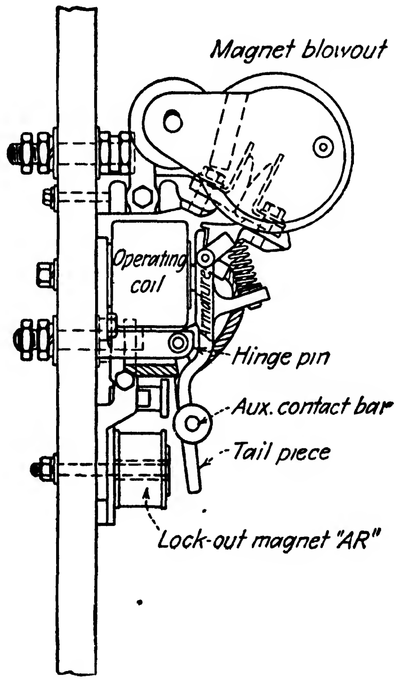


FIG. 86.—Cutler Hammer contactor with lock-out magnet under tailpiece. Contacts are in the closed position.

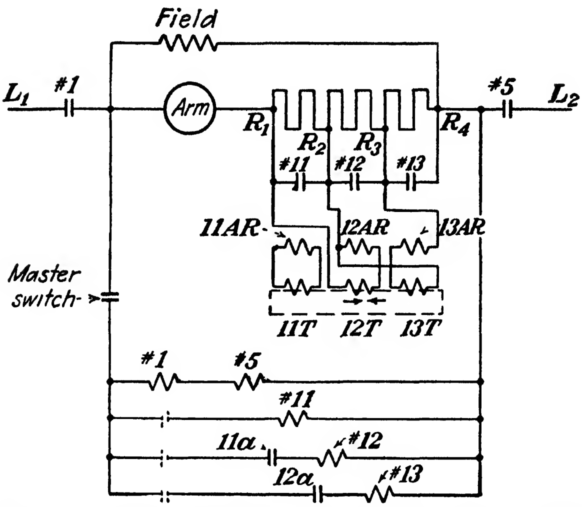


FIG. 87.—Magnetic time-delay acceleration using a transformer to energize the lock-out magnets.

To start, close the master switch. This closes 1 and 5 and energizes 11. Transformer 12T now predominates over 13T as R_1-R_2 is greater than R_2-R_3, giving 12T more voltage than 13T. Current is induced in 11T during the rise of flux. When the flux becomes constant, 11AR releases the contactor (Fig 86) and 11 closes. This short-circuits 12T, 13T, reverses the flux, and causes current to flow in 12AR. When the flux becomes constant, 12AR releases and 12 closes. This short-circuits 13T and the flux collapses, sending current through 13AR When the flux is gone, 13AR releases and 13 closes.

Coils 11AR, 12AR, and 13AR can be on relays (Fig 80), and hold open contacts in series with 11, 12, and 13 shown by the dotted lines instead of holding the contactors (Fig. 86) open. The timing can be adjusted the same as for Fig. 84.

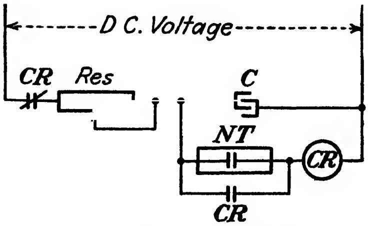


FIG. 88.—Diagram of timing device for relay CR, using a neon tube NT, a condenser C, and relay contacts CR.

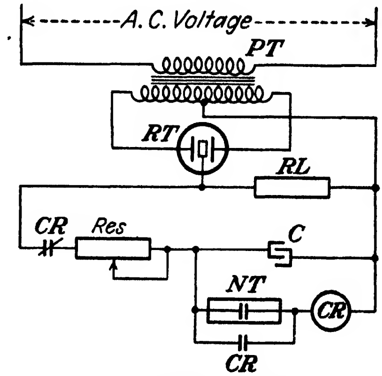


FIG. 89.—Diagram for obtaining d.c. power from an a.c. circuit for the timing device in Fig. 88.

release value. Figure 80 will illustrate a single- or double-coil switch or relay.

In the time-current accelerating relay shown in Fig. 82, when a current passes through the series coil the magnetic flux building up in the core and the frame induces a current in the aluminum tube, causing it to jump and open the circuit to a succeeding accelerating contactor coil. When the series current and the flux cease to build up, the aluminum tube starts to sink, but does this more slowly if the series-coil current remains large. For light starting loads the aluminum tube falls more rapidly. At the bottom of its stroke it bridges the stationary contacts

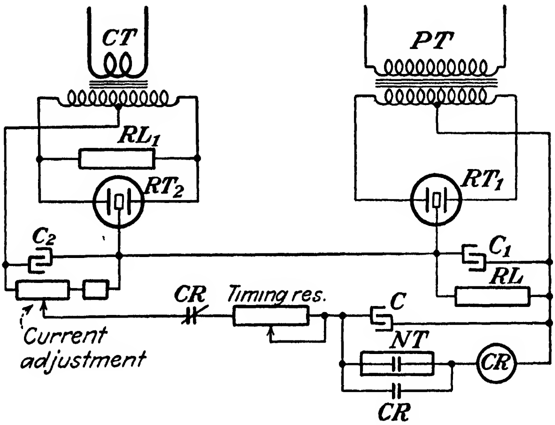


FIG. 90.—Diagram for obtaining current in addition to time control of relay *CR* shown in Fig. 89. This gives the time-current acceleration of Electric Controller and Manufacturing Company Neo-time-current starters for a.c. motors (Fig. 94).

to bring in the next accelerating contactor. The maximum time setting (2.75 sec.) with stalled motor current flowing in the series coil is obtained with the core screwed up into the frame flush with the locknut. Screwing the core down shortens the time interval for a given coil current. This relay, with some modifications, is used to prevent the plugging contactor from closing until the counter e.m.f. of the motor is reduced. It is connected across the plugging step of resistance.

An interesting application of the relay shown in Figs. 83*a* and *b* is a group of motors that cannot be started together after a voltage failure caused by lack of power, such as motors on an irrigation service line. A relay added to each motor control can be adjusted to start the motors at intervals. The General Electric Company's time-delay relay (Fig. 83*a*) is driven by a synchronous motor suitable for use on alternating current only. When the relay is energized, the solenoid engages the motor with the contact-operating mechanism; a tap on the solenoid provides the correct voltage for the motor. After the predetermined time interval has

elapsed, the normally open contact TC closes, the normally closed contact TO opens (see Fig. 83*b*), and the motor cutout switch disconnects the

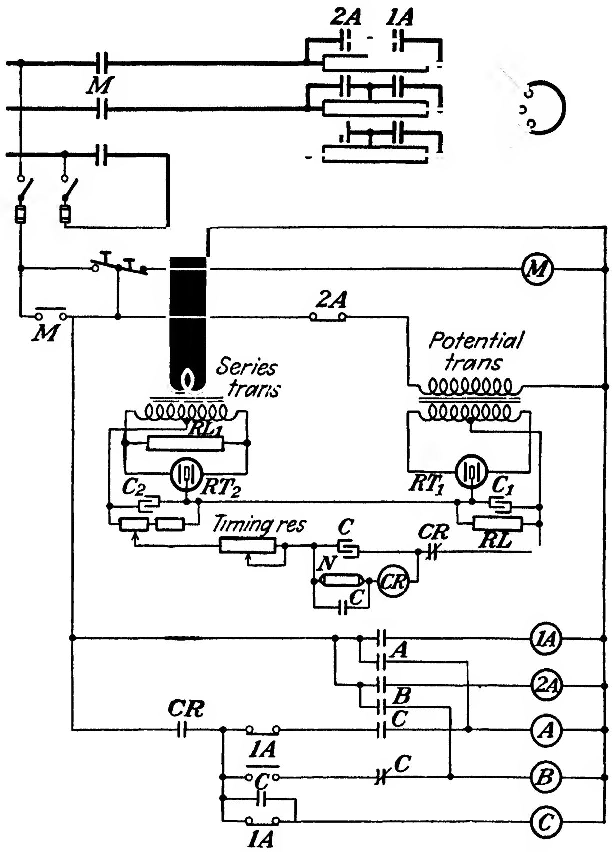


FIG. 91.—Neo-time-current acceleration for a three-step starter for squirrel-cage motor. The first operation of the *CR*, or timing relay, closes relay *C*, which holds itself closed as long as *CR* is closed and which, when operating, opens the circuit to relay *B* and closes the circuit to relay *A*, causing *A* to operate, which in turn holds itself closed and closes the first accelerating contactor 1*A*. If the timing relay *CR* should remain closed, even after 1*A* operates, it is impossible to close relay *B*, because *C* is still held in its closed position. Therefore, only one step of acceleration can come in on the operation of *CR* and, in order to get the succeeding steps of acceleration closed, *CR* has to drop out, which will occur after the condenser has discharged. When *CR* drops out, the charging circuit to the condenser is again established and relay *C* drops open. When the condenser has again become charged, it causes *CR* to operate for the second time, and this time *CR* will close relay *B* through the contacts of 1*A* and *C*. *B* will then hold itself closed and close accelerating contactor 2*A*, completing acceleration of the motor. Closure of contactor 2*A* opens the circuit to the timing transformer and prevents further operation of the timer while the motor is running.

motor. The contacts remain in the timed-out position until the relay is deenergized, at which time the solenoid drops out and the contacts are reset instantly to their original position.

An interlock contact J (Fig. 83a) is provided to establish a holding circuit when the relay is energized from a momentary-contact push button, as shown in Fig. 83b. This contact, which is normally open, closes when the solenoid is energized.

The time setting may be adjusted by releasing the locking spring B and turning the calibrating dial A until the locking spring is dropped into

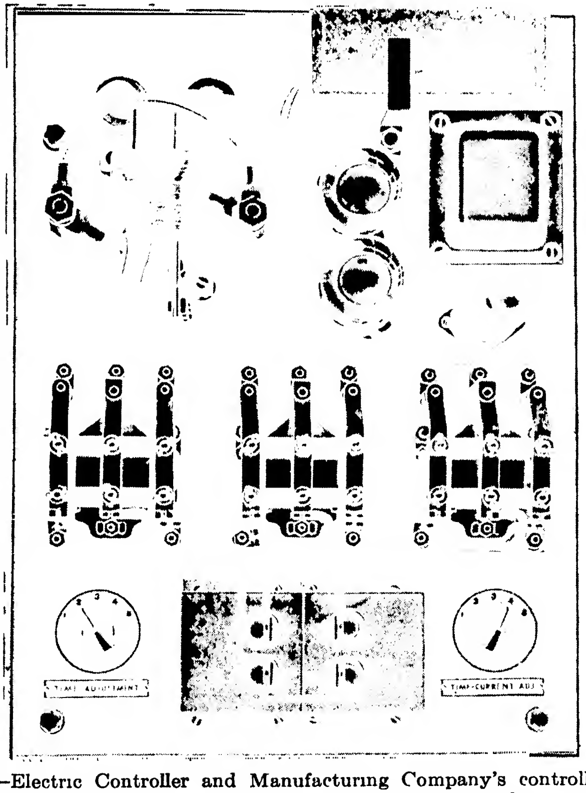


FIG. 92.—Electric Controller and Manufacturing Company's controller using condenser-timing and current limit. This is the master element for the controller shown in Fig. 93. This device is in the enclosed cabinet at the top of the controller.

the slot marked with the desired time. The dial is calibrated either in seconds or in minutes, depending on the maximum time obtainable.

Another type consists of a normally open switch, closed by a magnet and having a lock-out magnet attached to its tailpiece, to lock the switch open until the flux in the tail magnet dies out (see Fig. 86). The operation of the controllers using these three types of switches is explained in the captions under the diagrams.

The magnetic-delay method is free from friction, temperature, dirt, and moisture; its timing remains constant if the air gap does not change.

One size and design of relay can be used for controlling different sizes of contactors, which makes a good manufacturing and stocking arrangement. Standard contactors can be used.

This method of control is used for a.c. motors by rectifying the control-circuit current.

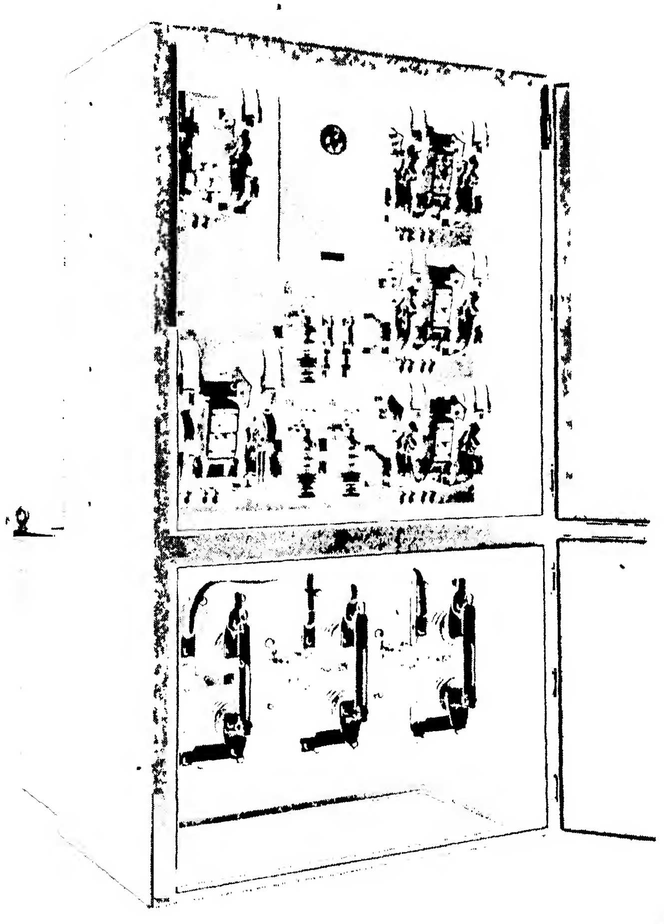


FIG. 93 A complete controller using the master element shown in Fig. 92.

Two pole contactors are required to short-circuit the resistance in the secondary of a slip-ring motor.

Figure 88, taken from H. L. Wilcox's paper before the A.I. & S.E. on Dec. 4, 1939, shows how a condenser C and a neon discharge tube NT can be used to time a relay with coil CR. When the voltage on the condenser

reaches the ignition voltage of the neon discharge tube NT, the condenser discharges through the tube and the coil, which causes the relay to "pick up," opening the charging circuit and closing a discharge circuit for the condenser around the tube and through the coil. The relay remains closed until the condenser voltage reaches the "drop-out" voltage of the relay. The relay then closes RCa and opens RC, and the cycle is repeated.

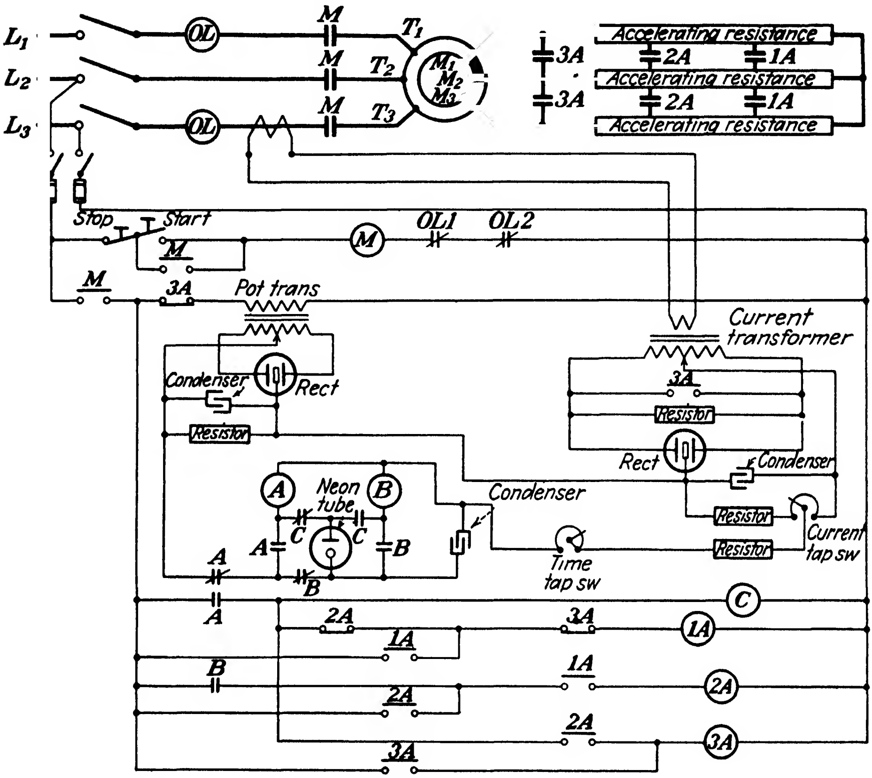


FIG. 94 Diagram showing Neo-time-current acceleration for a four-step wound-rotor induction motor of the Electric Controller and Manufacturing Company.

Other contacts can be added to the relay to actuate contactors when the relay is either Up or Down. When used with a.c. power, the d.c. power required for operating the relay can be obtained from a rectifier of the tube type (see Fig. 89) or of the copper oxide type. The relay CR can be combined with a potential transformer PT and a current transformer CT (see Fig. 90), to give time-current acceleration of a.c. motors. The current transformer opposes the voltage of the potential transformer, to increase the time required to operate the relay CR.

In the diagram shown in Fig. 90, PT is a potential transformer supplying voltage for the rectifier tube RT_1, similar in connections to the circuit

shown in Fig. 90. *CT* is a current transformer, the primary of which can be connected in the primary circuit of the motor or other device, while the secondary supplies voltage to a second rectifier tube RT_2. The connections are so made that the rectified voltage from tube RT_2 bucks

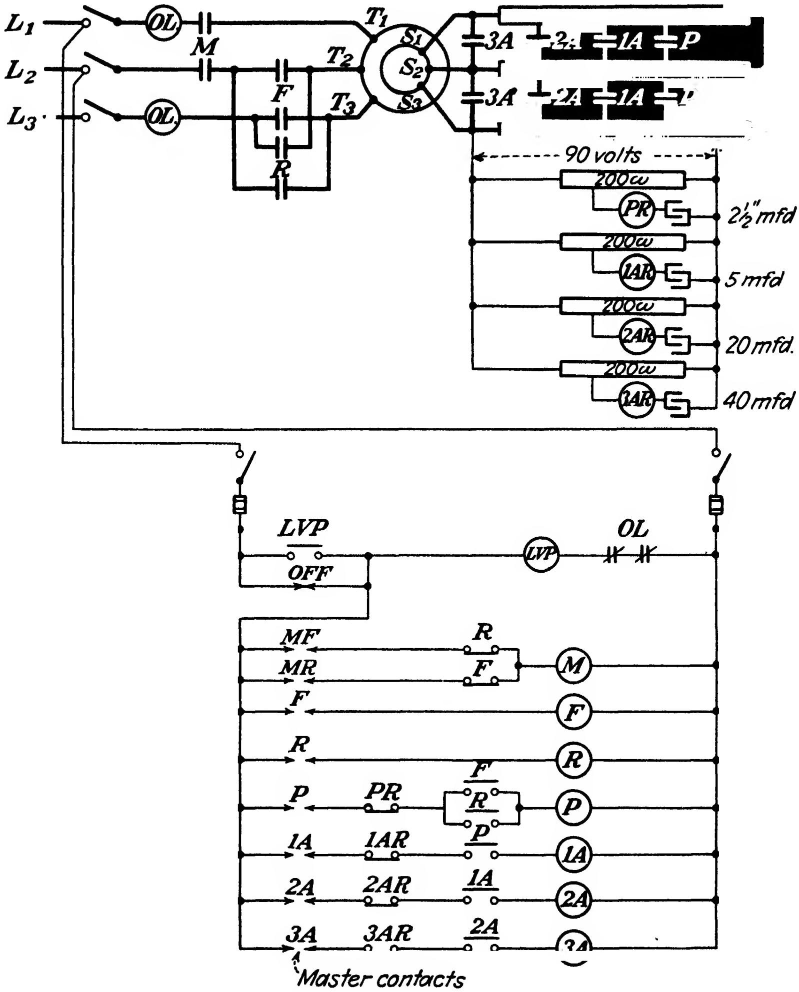


FIG. 95.—Diagram of a.c. controller using frequency relays to obtain automatic acceleration.

the rectified voltage from tube RT_1 and it is thus seen that, with higher currents in the primary of *CT*, the combined rectified voltage for charging the condenser will be reduced and, therefore, the time for the condenser to become charged will be increased. It is necessary in these connections to use load resistors *RL* and RL_1, also two filter condensers C_1 and C_2,

which cause the two rectified voltages to remain in phase. By shifting the current adjustment tap on the resistance supplied with the *CT* timing element, it is possible to increase or decrease the amount of bucking effect, and, therefore, to increase or decrease the amount of current effect upon the timing.

FREQUENCY CONTROL FOR ACCELERATING A.C. WOUND-ROTOR MOTORS

When a 60-cycle a.c. wound-rotor motor is accelerated, the secondary frequency decreases from 60 cycles at zero speed to two or three cycles

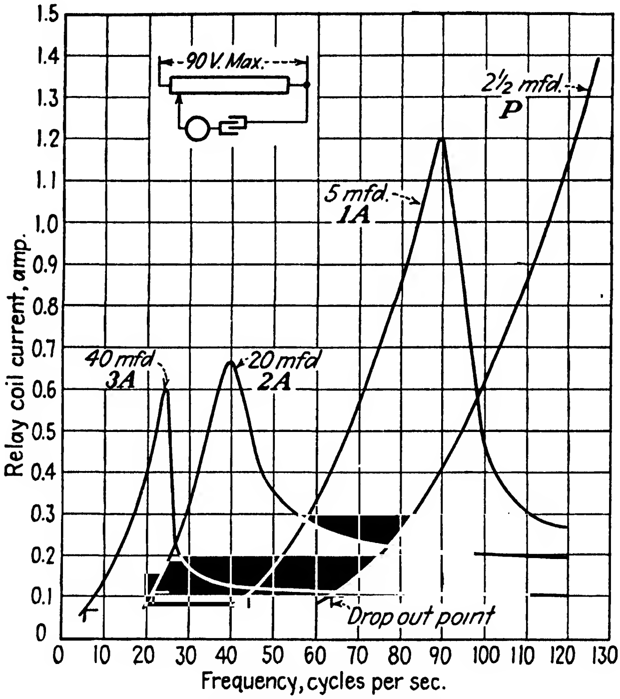


FIG. 96.—The drop-out points of relays when the frequency decreases during acceleration of a wound-rotor induction motor (Fig. 95). These points are at 63, 44, 22, and 6 cycles.

at full speed and the voltage between phases also decreases in the same proportion. The Electric Controller and Manufacturing Company has developed a frequency-relay system responsive to this frequency and voltage change to control the short circuiting of the secondary resistor in steps, in accordance with the motor speed shown in Fig. 95. Use is made of the principle of resonance to hold relays open until the desired frequency is reached. Each relay coil has a condenser in series with it and both are in parallel with part of an adjustable resistor, as is shown in the diagram. The condensors are given different capacities to make

the relays drop out at 63 cycles for plugging, 44, 22, and 6 cycles for acceleration. Figure 96 shows the current curve of each relay and its drop-out point.

Both the diagram and the curve are taken from the paper by H. L. Wilcox, previously referred to. This paper describes many details of the control. The relay inductance is different at open and at closed gap, so that the relay "drops out" at a higher current than it "picks up."

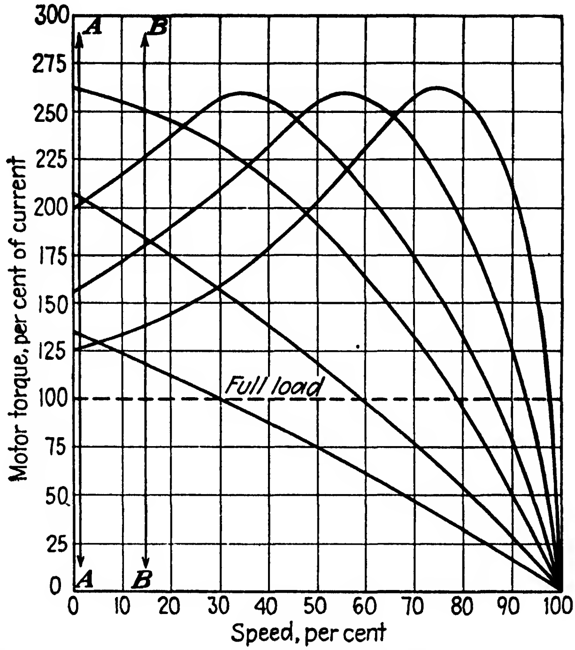


FIG. 97.—Speed-torque curves of a wound-rotor induction motor. Each curve has a different amount of resistance in the secondary circuit. The last curve to the right has no external resistance and the secondary windings are short-circuited.

Should the load on the motor increase above normal, the secondary current will increase, the relay will pick up, and the secondary resistance will be increased. From Fig. 97, showing the speed-torque curve of a wound secondary motor, it will be seen that for each step of resistance added, the motor speed is reduced; this usually reduced the load. The motor will be automatically accelerated to full speed again when the load returns to normal. The curves also show that the resistor should not be reduced faster than the motor accelerates, as this will reduce the torque and the motor may "pull out." When the load has a flywheel, these relays can be used to "step back" on the resistor to let the flywheel take part of the load and keep the current peaks down.

CONCLUSION

The selection of the proper method of accelerating a motor depends upon the application, the voltage regulation of the power supply, the first cost, and the preference of the purchaser.

Customer preference shifts from one type to another and all have their limitations—a circumstance that influences the situation. Often several different methods of acceleration are equally satisfactory for the same application. Usually the type having the lowest first cost is preferred in the general-application field. More expensive types are justified in special fields, as they reduce the maintenance expense and shutdown time. Time delay is preferable where the line voltage fluctuates. The increment starting required for large motors connected to network systems uses definite time-delay acceleration. The counter e.m.f. system requires the least apparatus.

The series lock-out contactor, which was once very popular in steel-mill service, is not used much at present. The popular method now is time delay.

CHAPTER VII

METHODS OF SPEED CONTROL

DIRECT-CURRENT VARYING-SPEED MOTORS

Variations in the speed of a d.c. motor can be obtained by changing the voltage across the motor brushes. Usually this is accomplished by placing a resistor in series with the armature, as shown in Fig. 98. The drop in voltage through the resistor is equal to the resistance multiplied by the current. If the line voltage remains constant, the speed of the motor can be varied by changing either the ohmic resistance or the load. The characteristic curves for d.c. shunt, compound, and series motors are shown in Fig. 99. Curve *A* is for a shunt motor. The difference in

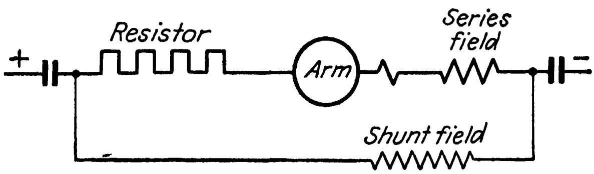


FIG. 98.—Diagram of connections for varying speed of d.c. motors that use a resistor in series with the armature.

speed between full load and no load is caused by the drop in voltage due to the internal resistance of the motor. The amount of change in speed is called the regulation of the motor, which may be expressed by giving the speeds at no load and at full load or as a percentage change in speed. The shunt motor is assumed to have a constant field strength; therefore, the change in speed is small. If, however, a resistor is placed in series with the armature, a curve such as *AA* is secured, which shows considerable reduction in speed at full load, the amount of speed reduction depending upon the resistance in series with the armature. In this case, it can readily be seen that the speed of the motor depends upon the load and will vary with different values of torque. For this reason these motors are called "varying-speed" motors.

If part of the field winding is made up of series turns, the field strength will increase with increased torque, so that the difference between no-load and full-load speed is quite marked, as is shown by curve *B*. If external resistance is used, a curve such as *BB* results. This curve can be changed by varying the amount of resistance in series with the armature. Curve *C* shows the regulation curve of a series motor. Theo-

retically, at no load, there is zero field strength and, therefore, infinite speed. Consequently, it is necessary to have a definite load on a series motor to prevent its running away, and series motors should not be used for any applications where the load is reduced to a very small value. Usually 25 per cent of full load is required to keep the speed within safe limits. If a resistor is used in series with the armature, curve *CC* results, which can be varied by changing the resistor.

It will be seen from these curves that the series motor is best adapted for speed regulation by the use of series resistance, the slope of its curve being much steeper than those for the shunt and the compound motor. Where the load may become very light at times, it is necessary either to

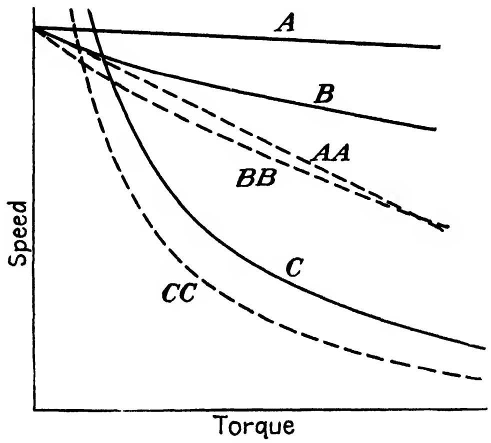


Fig. 99.—Characteristic regulation curves of d.c. motors that use the series resistor scheme in Fig. 98.

make a special arrangement for energizing the series field, as will be explained later, or to use a compound motor. The curve for the compound motor will vary between that of the series and that of the shunt motor, depending upon the percentage of compounding used.

With this method of speed control, it is necessary to change the amount of armature resistance to obtain the correct speed with a changing load. This at first sight may seem to be rather complicated, but in practice the operator can move his controller lever forward or back until the desired speed is obtained.

Where it is desirable to regulate the speed of the motor within closer limits, the arrangement of resistors shown in Fig. 100 is used, where *RA* is a resistor in series with the armature and *RS* is a resistor in shunt with the armature. This is known as a combined armature-series and shunt-resistance control. If *RS* has a very low ohmic resistance, the speed of the armature can be held at a low value throughout its range

of load. Figure 101 shows the various curves for this arrangement. Curve 1 is the armature current. Curve 2 is the line current, and curve 3 is the shunt current passing through the resistor *RS*. Curve 4 is the speed-current curve for the motor connected directly to the line. It can be seen from these curves that the motor performance is somewhat similar to a badly regulated shunt motor. At no load, the series field

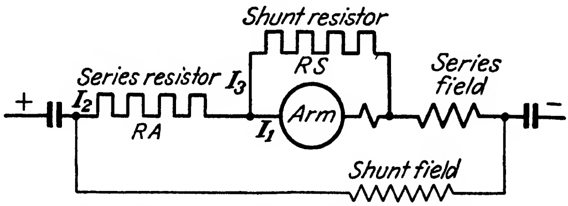


FIG. 100.—Diagram of connections for speed regulation that use the combined series and shunt resistance control method.

obtains current through the resistors *RA* and *RS* so that the speed of the motor has a fixed value. The speed can be changed by varying either *RA* or *RS*. Sometimes both are changed simultaneously. In figuring the speeds obtained with this arrangement, the circuit is rather complicated. The problem can be simplified by drawing curves similar to the ones shown in Fig. 101. Two points in these curves can readily be determined. The armature and line current can be found for zero load

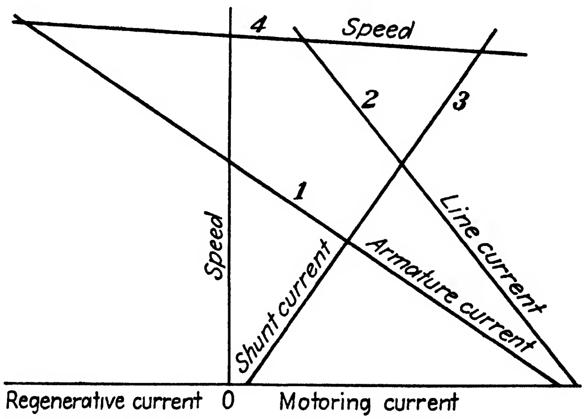


FIG. 101.—Characteristic curves of d.c. motors that use the control scheme in Fig. 100.

and for zero speed. The shunt current in resistor *RS* can be figured from these two values.

DIRECT-CURRENT ADJUSTABLE-SPEED MOTORS

If the internal resistance of the armature is neglected and if it is assumed that the number of conductors on the armature is fixed, the

speed of the motor will depend upon the strength of the field, provided that a constant voltage is maintained across the armature brushes. If the motor is shunt wound and a rheostat is placed in series with the field winding, the current can be changed and the motor caused to operate at different speeds. The speed of the motor will be practically constant for whatever value the rheostat is adjusted and will not vary under changing loads. For this reason, the motor is called an adjustable-speed motor. There will be a small change in speed between no load and full load, owing to the drop through the armature resistance. This change in speed, however, is usually negligible for most applications. The amount of speed range that can be obtained on a given motor depends upon the iron in the magnetic circuit. The slowest speed is obtained with the maximum field strength. This field strength, of course, reaches a limit when the iron in the magnetic circuit becomes saturated. The maximum speed is obtained with the weakest permissible field strength. This can be reduced only a limited amount, as sufficient field must remain to give stable operation of the motor. To obtain a wide speed range by field control involves considerable expense in the motor, and usually a maximum of four to one is all that is attempted commercially.

For many applications, the combination of armature resistance and field control is used. The slow speeds are often required for only short intervals of time or at reduced loads, so that the loss in armature resistance is small.

DIRECT-CURRENT MOTOR VARIABLE-VOLTAGE CONTROL SYSTEM

If a separate generator is provided for each motor, the speed of the motor may be altered by changing the field strength of the generator. This alters the voltage of the generator and the motor has a speed corresponding to the generator voltage. The generator field may be reversed to reverse the rotation of the motor. Very slow speeds can be obtained and the speed remains fairly constant between no load and full load. In the past, this method of control has been reserved for large motors of several hundred horsepower, being particularly adapted for reversing service, as for large mine hoists and reversing steel mills; but recently it has been successfully extended to smaller motor installations, such as elevators, reversing planers, etc. The controller is small and inexpensive, as only the field current of the generator is manipulated. It is the practice to connect the generator and motor armatures in a closed circuit provided with a single overload circuit breaker, which is opened only in cases of emergency. Electron tubes can be used instead of the Motor-Generator Set. See Chap. XIX.

Sometimes this arrangement of control is combined with a motor having a two-to-one speed range by field control, so that higher speeds

can be obtained for certain operations. The initial cost of this combination is less than that of the constant-speed motor, as it does not add a great deal to the cost of the motor to obtain the additional increase in speed, and a smaller generator can be used than would be required if the entire speed range were obtained by varying the generator voltage.

A more detailed discussion is given in Chap. XI.

ALTERNATING-CURRENT VARYING-SPEED MOTORS

The relation between the speed and the torque of an induction motor having a wound secondary with collector rings is shown in Fig. 102.

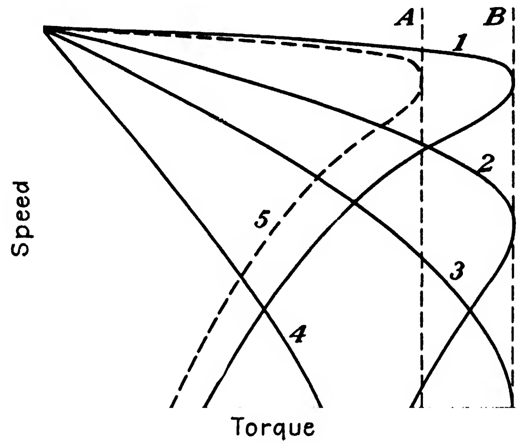


FIG. 102.—Typical speed-torque curves of a wound-rotor induction motor. Obtained by varying the resistance of the secondary circuit.

When the collector rings are short-circuited, the speed of the motor decreases very little from no torque to the maximum torque. When this torque is exceeded, the speed of the motor drops abruptly and continues to decrease until zero speed is reached. If, however, the torque is sufficiently reduced, the motor will again increase in speed until it is very close to full speed. The curve shows that there is a maximum torque that the motor is capable of exerting and that, if this torque is exceeded, the motor will stop. This maximum torque is usually called the "pull-out torque" of the motor. The drop in speed from no load to maximum load is small and compares with that of the d.c. shunt motor. This drop in speed is due to the internal resistance of the motor.

If resistance is introduced in the secondary circuit of the motor, the slope of the speed curve is increased, so that the difference in speed between no load and maximum load is considerable, as shown in curve 2. Sufficient resistance can be used to bring the speed to zero at the maximum torque, as shown in curve 3. With a still further increase in

resistance of the secondary, curve 4 results. These curves are typical, and any particular curve desired can be obtained by adjusting the resistance in the secondary circuit of the motor. If a controller is arranged for varying the resistance in the secondary of the motor, the speed of the motor can be adjusted to any required value at a given torque. The speed, however, will change with the torque, and for that reason the motor is called a "varying-speed" motor.

When the motor is started from rest, it may not commence to rotate on the first notch of the controller; the operator will, therefore, move the controller handle to the second notch to reduce the resistance in the secondary. This reduction of resistance will increase the starting torque

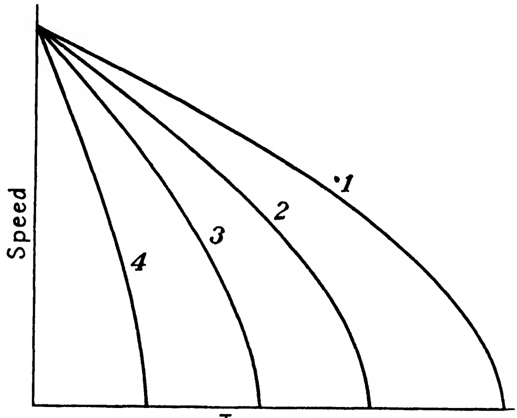


Fig. 103.—Typical speed-torque curves of a squirrel-cage induction motor. Obtained by primary voltage control.

by changing the shape of the curve up to the point of maximum, as shown in curve 3. If the resistance is reduced still further, the current will increase, but the torque will decrease, as shown in curves 2 and 1. Hence, it will be seen that care must be exercised in starting these motors under heavy load, to prevent reducing the resistance in the secondary beyond the value for maximum torque.

The speed of the motor at no load is called the "synchronous" speed. When the motor is loaded, the actual speed of the motor is less than the synchronous speed. This difference in speed is called the "slip" of the motor. The curves show that this slip in speed is dependent upon the resistance in the secondary circuit.

The torque of the motor is proportional to the square of the voltage. A reduction of 10 per cent in voltage reduces the torque to 81 per cent of its maximum value, or the pull-out torque of the motor is reduced from the dotted line B in Fig. 102 to the dotted line A. The speed-torque

curve of the motor with short-circuited secondary and 90 per cent normal voltage is shown by the dotted curve 5. Thus the output of a crane or a hoist is often seriously affected by poor voltage regulation. It may happen that when the voltage regulation is poor the motor will fail to start its maximum load from rest.

If the motor is provided with a high-resistance secondary, as shown in Fig. 103, curve 1, which is a speed-torque curve similar to curve 3 in Fig. 102, the speed of the motor may be regulated by reducing the primary voltage, as shown in Fig. 103, curves 2, 3, and 4. This method has been employed, but has the disadvantage of giving reduced torques at decreased voltages. Usually the motor is required to exert as much torque at the slow speed as at the high speed; this method is, therefore, seldom used. The method in universal use at present for varying the speed of induction motors is to maintain the primary voltage constant and change the resistance in the secondary of the motor.

There are several other methods of controlling the speed of the slip-ring induction motor, some of which are applicable only to large motors. They consist in connecting the slip rings of the motor to some source of voltage supply the voltage and frequency of which can be varied. These methods of control are not yet in common use (see Chap. XIII).

ALTERNATING-CURRENT ADJUSTABLE-SPEED MOTOR

The best known means at present for adjusting the speed of a.c. motors is to change the number of poles in the primary. Quite frequently, motors are built having two sets of poles, one set giving high

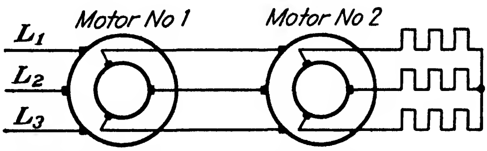


FIG. 104.—Cascade connection of induction motors for speed regulation.

speed and one set slow speed. Usually these motors are provided with squirrel-cage secondaries, but slip-ring motors also have been built of this type, particularly for elevator and hoist work. The controller consists of a double-throw switch or its equivalent for changing the connections of the motor primary so as to give the desired number of poles.

Another method, which is equivalent to changing the number of poles, consists in connecting two motors in cascade, the secondary of the first motor being connected to the primary of the second, as shown in Fig. 104. Let us consider that the first motor is wound with six poles

and the second motor with four poles. These motors can be connected together, so that they have a combined speed equivalent to the sum or difference of the poles, which would be a ten-pole or a two-pole speed. Either motor can be operated separately as a six-pole or a four-pole motor. With this combination it is possible to get a speed equivalent

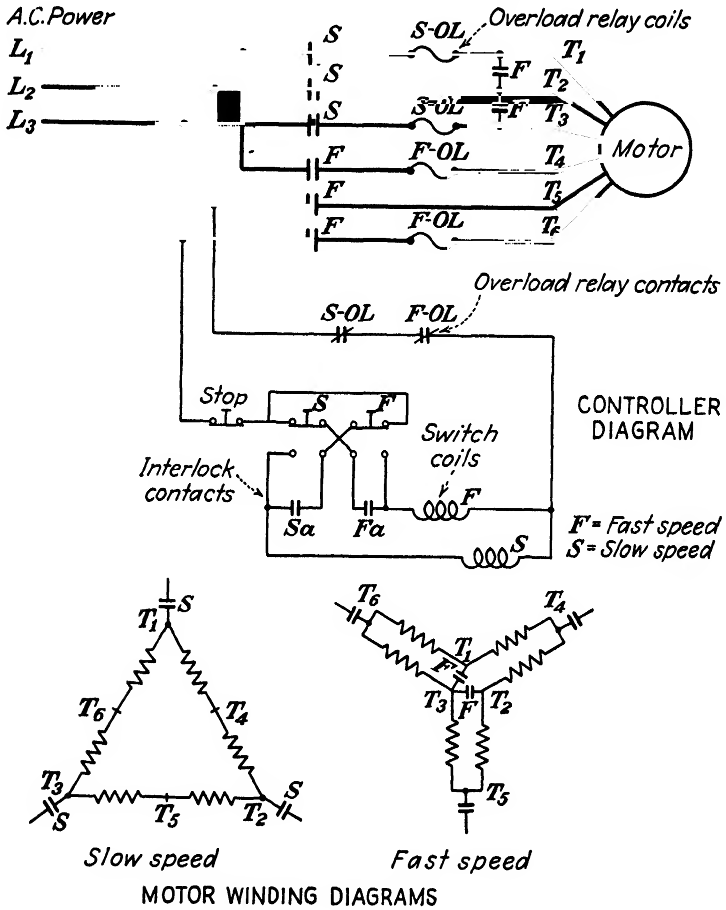


FIG. 105.—Diagram of a two-speed single-winding squirrel-cage induction motor showing the controller contacts. *S* contacts give slow speed; *F* contacts give fast speed.

to two, four, six, and ten poles. It is necessary that both motors be mounted upon a common shaft or rigidly coupled together. Arrangements of this kind have been used in a number of cases, particularly with large motors.

A two-speed motor may have two separate windings or a single winding arranged so it can be connected to give two sets of poles in the ratio

of 2 to 1. Three-speed motors usually have two windings. Other speed ratios usually require two separate windings.

Three-speed motors usually have three separate windings. Four-speed motors may have two windings, each group of two giving a 2 to 1 speed ratio. Many of the smaller machine-tool and fan motors have multispeed windings. When stepping back from a higher to a lower speed, the motor will regenerate until it reaches the slower speed. This gives a sharp reverse torque, which may be guarded against if it is undesirable, by opening the circuit until the speed is reduced. Figure 105 shows a schematic diagram of connections for a two-speed motor.

In a later chapter other methods of adjusting the speed are described.

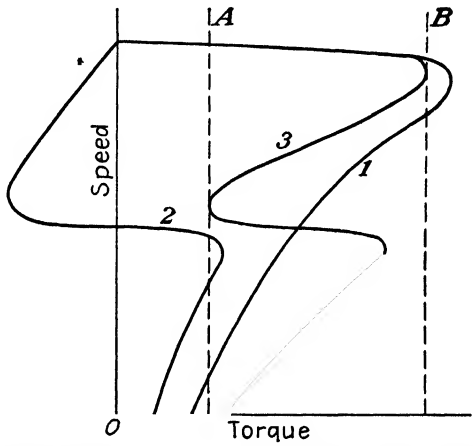


FIG. 106.—Typical speed-torque curves of a polyphase motor that has a single-phase secondary winding.

A special condition of operation exists in the slip-ring type of induction motor when one phase of the secondary circuit is open. This gives a single-phase circuit only in the secondary, and the motor operates at approximately half speed over a considerable range of load. The explanation of this is shown in Fig. 106. Curve 1 represents the standard speed-torque curve set up by the primary, and curve 2 the speed-torque curve of the single-phase secondary. Curve 3 is the resultant of 1 and 2. As curve 2 passes through half speed it approaches a horizontal position; therefore, a slight change in the speed of the motor results in a considerable change in torque, which tends to maintain the speed constant at this value. If the motor is started from rest and the load is not too heavy, it will accelerate to half speed and remain approximately at this speed, unless the external torque is less than the value shown by the dotted line A. If the torque is less than this value, the motor will continue to accelerate on the upper part of curve 3 and approach full speed. After

the motor has reached the upper part of curve 3, it will not again be brought to half speed unless the primary circuit is first opened, thus allowing the motor to drop down below half speed. However, the motor will stop if the load exceeds the dotted line *B*. The value shown by the dotted line *A* depends upon the secondary resistance of the motor and a number of other factors. This arrangement of speed control might be applicable for fans, where the torque depends largely upon the speed.

CHAPTER VIII

CONTROL FOR SPECIAL APPLICATIONS

Some applications require modifications of standard control to meet their particular requirements. A few of the more common features of these special-purpose controllers are given below in the form of simplified diagrams.

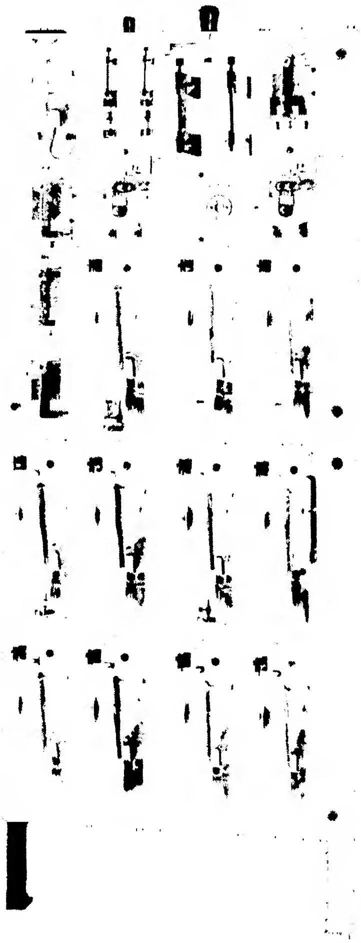


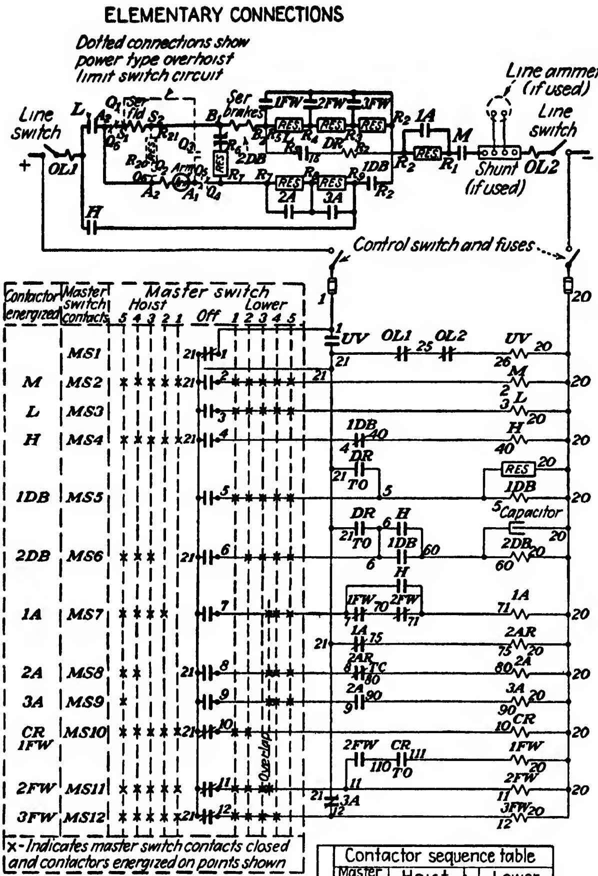
FIG. 107.—Westinghouse d.c. magnetic controller for crane service.

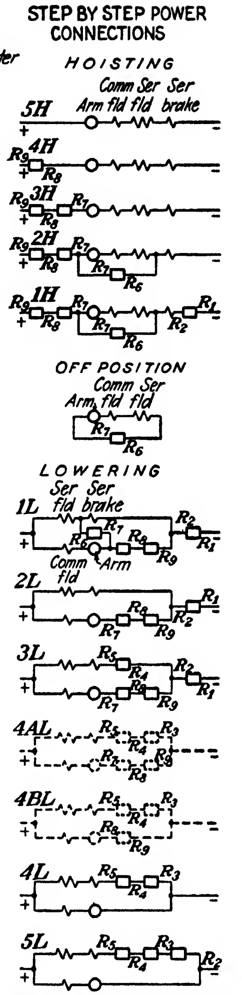
CRANE CONTROL FOR D.C. SERIES MOTORS

During the hoisting cycle, an armature shunt resistor is used for slow speed in connection with the series resistor.

A dynamic brake is used in the Off position. During the lowering cycle the motor operates as a shunt machine. With an overhauling load, the motor becomes a generator and the armature circuit is closed through a resistor, to absorb the power delivered by the generator. This action is referred to in Chap. IX under Dynamic Braking. Figure 108, with the sequence table, shows the General Electric design arrangement, and Fig. 109 gives the performance curves. Different manufacturers use modified arrangements but follow the same principle, *i.e.*, a series hoist motor and a shunt motor or generator for lowering. Figure 110 compares four different systems. One problem is to obtain a high lowering speed with an empty hook.

In studying a diagram such as Fig. 108, use the sequence table to draw a diagram for each controller notch, as illustrated at the right-hand





Contactor	Master handle position	Hoist 5	Hoist 4	Hoist 3	Hoist 2	Hoist 1	Off	Lower 1	Lower 2	Lower 3	Lower 4	Lower 5
	M	x	x	x	x	x		x	x	x	x	x
	L							x	x	x	x	x
	H	x	x	x	x	x						
	1DB							x	x	x	x	x
	2DB				x	x	x	x				
	1A	x	x	x	x						x	x
	2A	x	x								x	x
	3A	x									x	x
	1FW	x	x	x	x	x	x	x	x			
	2FW	x	x	x	x	x	x	x	x	x		
	3FW	x	x	x	x	x	x	x	x	x	x	

Contactor sequence table. x Indicates contactors closed

The above power connections are obtained on the various points of the master switch hoist and lower. The circuits shown solid are both hand as well as automatic points. Circuits 4AL and 4BL, shown dotted, are automatic accelerating points only

FIG. 108.—General Electric control diagram for a d.c. crane controller.

side of the diagram, omitting the switches and the resistor sections not used. This will quickly show you the sequence of the control operations and the way they work.

When a.c. motors are used for cranes and hoists, they require a mechanical load brake to absorb the energy when the load is lowered. This brake requires the motor to deliver some positive torque to assist

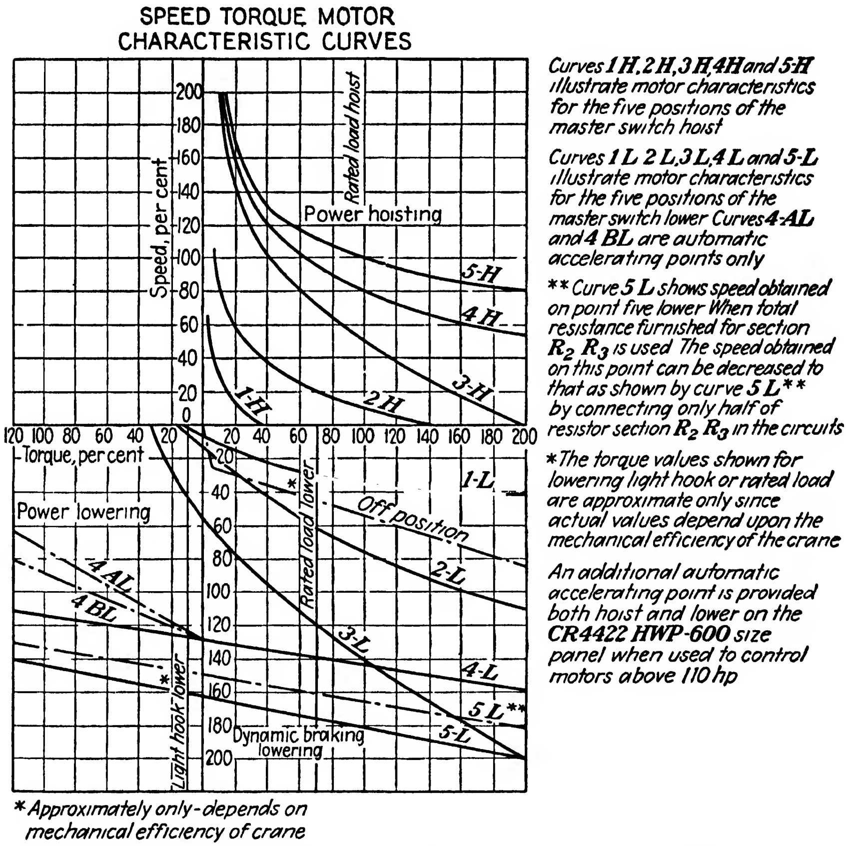
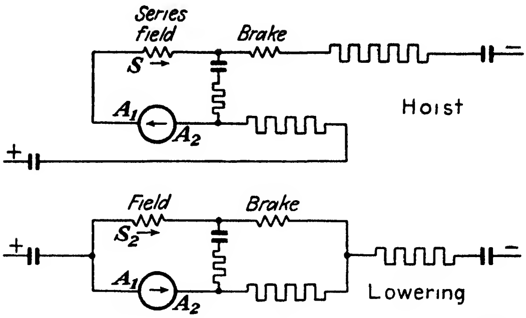


FIG 109 —General Electric performance curves of a d.c. crane motor using the controller in Fig. 108.

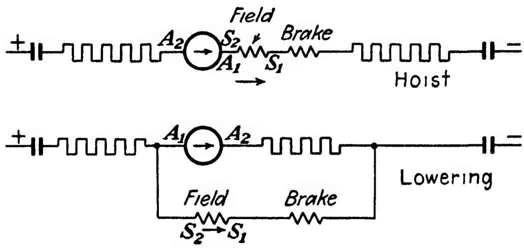
the load in unwinding the drum so that the speed can be readily controlled. If the motor secondary is connected single phase on the first controller notch, the starting torque will be about one-half of that obtained with a three-phase secondary of the same resistance.

Figure 95 shows a controller diagram suitable for a crane or a hoist using a wound-rotor a.c. motor.

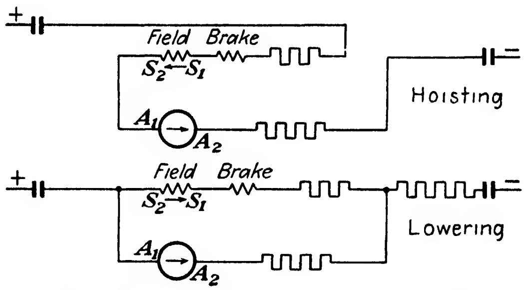
Figure 97 shows the speed-torque curves of a wound-rotor a.c. induction motor.



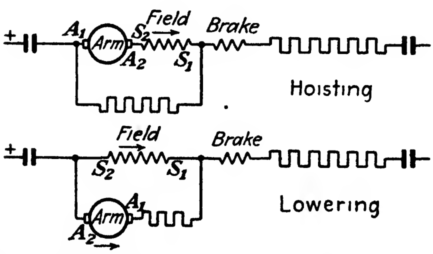
General Electric system. The armature is reversed.



Cutler-Hammer system. The armature is reversed.



Westinghouse system. The field is reversed



Electric controller and Manufacturing Company's system. The armature is reversed.

FIG. 110.—The connections on the first controller notch used by four controller companies (1943). The resistors are changed for the other controller notches to get higher speeds. Each arrangement differs from the others in a few details.

PUMP CONTROLLERS

Pump controllers are ordinary starters actuated by a special master switch, such as a pressure gauge or a float. Speed control, if it is required, can be obtained in any of the usual ways.

The starting and stopping of an air compressor by a pressure switch or of a fan by a thermostat is accomplished in the same way.

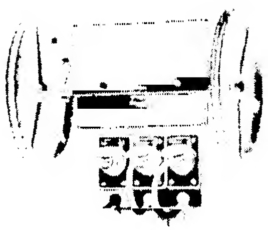
Small pumps driven by squirrel-cage motors can be started by connecting the motor directly to the line. Only a primary switch is required. Large motors may use an autostarter, when they are started and stopped infrequently. For frequent starting and stopping, a slip-ring motor or a compound d.c. motor should be used. For d.c. service, the compound-wound motor gives the best results for either centrifugal or plunger pumps. For the two latter types of motors, an ordinary nonreversing rheostatic control is used, consisting of a line switch for connecting the motor to the circuit, and one or more contactors for short-circuiting the starting resistor. The line switch is usually provided with an overload relay or, if the control is manually operated, the line switch may be an ordinary circuit breaker. Low voltage release is usually supplied with automatic control, as it is desirable to have the motor start automatically upon reestablishment of the power circuit after an interruption. The master switch may consist of a push button or, where speed regulation is desirable, a drum-type master switch can be used. It is usual, however, to start and stop pumps automatically. The automatic means may be actuated by pressure or by the height of the water in the reservoir or tank; the latter is known as a "float switch."

Fig. 111.—Cutler-Hammer pressure regulator of the diaphragm type.

Pressure Regulators.—Two general forms of pressure regulators are used, the Bourdon gauge and the diaphragm type. The gauge type consists of the ordinary indicating pressure gauge with a contact make-and-break device attached to the indicating needle. Some modifications in the standard gauge are required for the addition of this contact device. In order to reduce the arcing at the contact points, a relay is used. This relay is connected so that, when it closes, it bridges the low-pressure contact on the pressure gauge and prevents an arc at this contact when the gauge needle moves to a higher pressure. The high-

pressure contact is arranged for short-circuiting the coil of this relay, which immediately opens the relay and at the same time opens the circuit through the gauge contact. When a resistance is placed in series with the relay coil, this short-circuiting can take place without danger of excessive current.

The diaphragm regulator consists of a metal diaphragm having pressure on one side and a weight or spring on the opposite side (see Fig. 111). The diaphragm is raised or lowered, with variations in the water pressure. This movement of the diaphragm mechanism closes or opens the contacts of the master switch. The diaphragm regulator



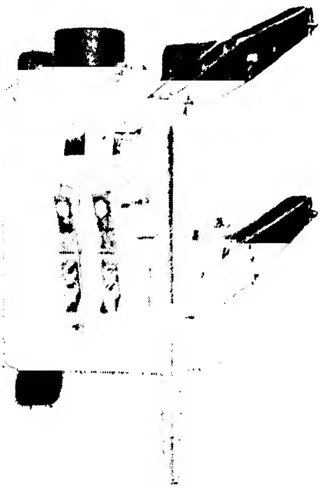


Fig. 112.—Cutler-Hammer float switch.

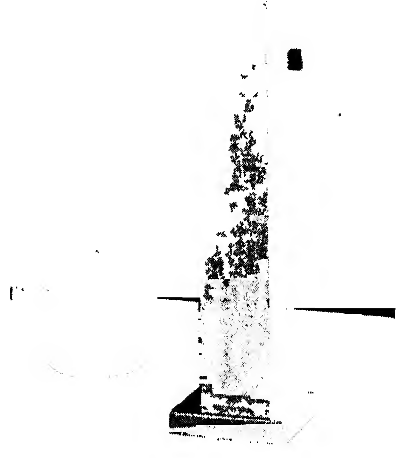


Fig. 113.—Cutler-Hammer multipoint float switch.

ordinarily does not require a relay, as the contacts are large enough to take care of the control circuit of an ordinary-sized contactor.

When a pressure regulator is used with a positive-acting pump, it should not be connected directly to the pump delivery, as the pulsations cause the regulator to open and close the contacts in rapid succession and give very poor results. Usually, the pump delivers to a pressure tank or standpipe, and the pressure regulator can be connected to the tank or standpipe. Where the pump delivery is long and it is not convenient to connect the pressure regulator in this way, special precautions

should be taken to prevent the regulator from being oscillated by the pulsation in the pump delivery.

Float Switch.—The master switch of the float type consists of a small contact that is opened or closed according to a difference in the level

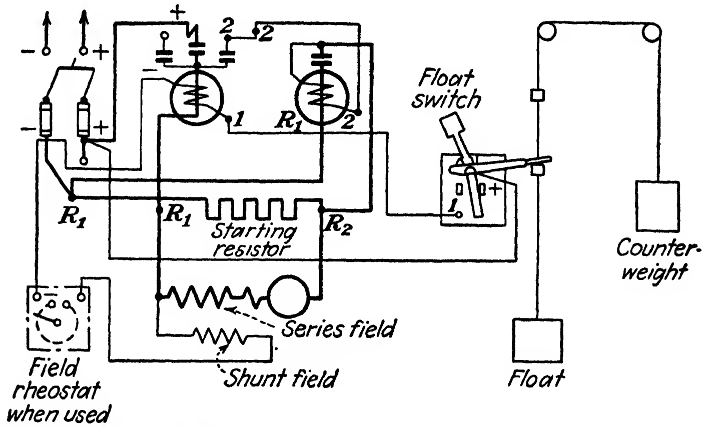


Fig. 114.—Connections of a two-point d.c. automatic-pump controller operated by a float switch.

of the water in the tank or reservoir. One form of this switch is shown in Fig. 112 and another in Fig. 113. The contacts are provided with a quick make-and-break arrangement, so that the slow movement of the float does not cause arcing. This float switch is connected to the pilot

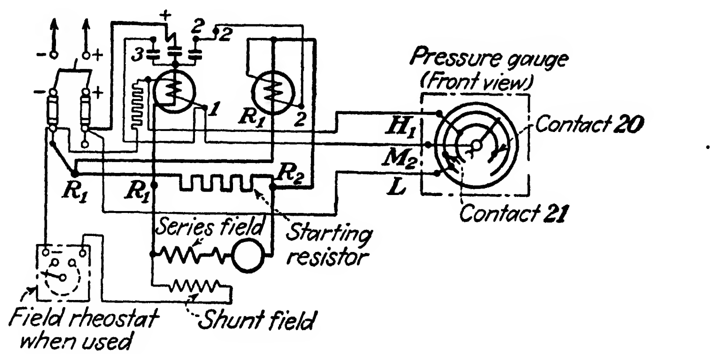
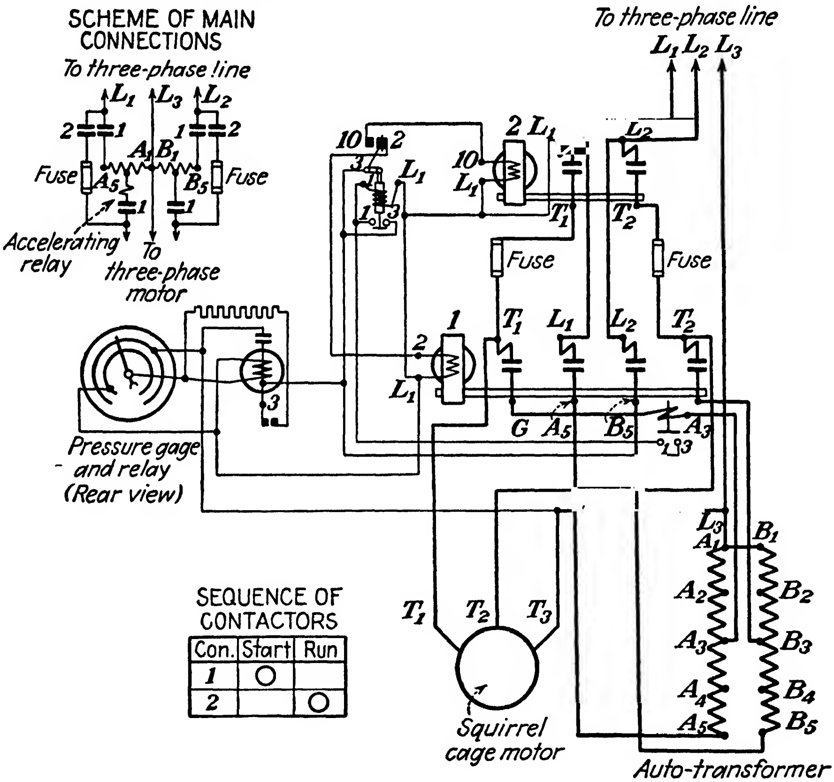


Fig. 115.—Connections of a two-point d.c. automatic-pump controller operated by a pressure gauge.

wiring of the controller and serves to start and stop the motor according to variation in the water level. If this float switch is used in a reservoir where large waves are likely to occur, it should be mounted in an enclosed compartment to protect it from the wash.

ELEVATOR PUMPS

Elevator service is a special application. Hydraulic elevators are usually operated in banks comprising several elevators connected to a single pressure tank. The elevators discharge into an open tank and the pump takes the water from the open tank and delivers it to the pressure tank. For large installations, several pumps are used. The



Con.	Start	Run
1	O	
2		O

FIG. 116.—Connections of an automatic autostarter for a squirrel-cage pump motor operated by a pressure gauge.

pumps are controlled by pressure regulators which start and stop the pump for variations in pressure. During some portions of the day, the pump is operated at infrequent intervals, as the elevator service is light. At other times, particularly the noon hour and the closing hour in the evening, office-building elevator pumps are started and stopped frequently, sometimes two or three times a minute, and this entails a considerable shock upon the system. One method of overcoming this difficulty is to slow the pump down, rather than to stop it, when the pressure reaches a predetermined value. If a positive-acting pump

is used, considerable power may be lost by such an arrangement, as the water pumped is directly proportional to the speed of the pump. To reduce the output one-half, the pump must operate at half speed, which

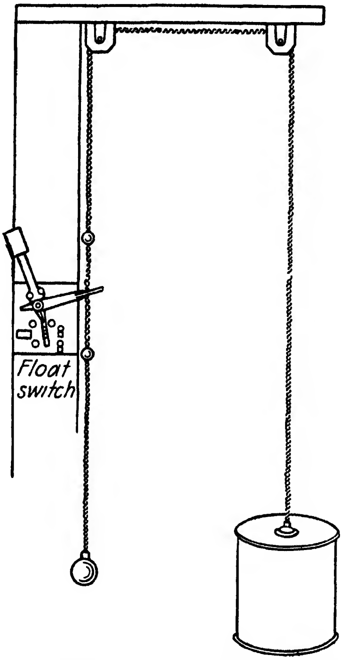


FIG 117.—Arrangement for operating a float switch.

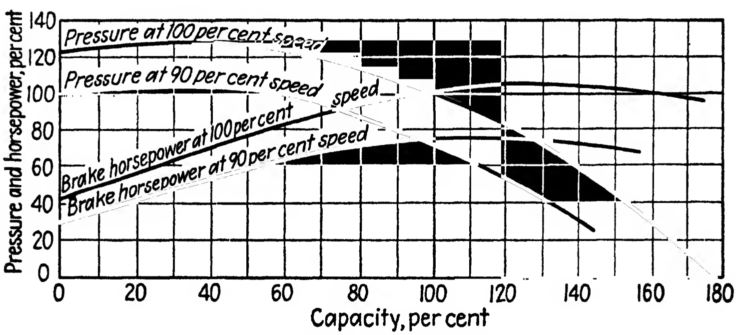


FIG. 118.—Typical capacity and horsepower curves of a centrifugal pump showing the effect of a 10 per cent speed variation.

causes a loss in resistance equal to half the electric power delivered to the motor. If centrifugal pumps are used and designed for this service, a small change in speed will make a large change in water delivery. The

curves in Fig. 118 represent the gallons of water delivered by a typical pump with reference to the speed of the pump. This shows that a small reduction in speed makes a large difference in the output and that, therefore, by the insertion of a small amount of resistance in the motor circuit,

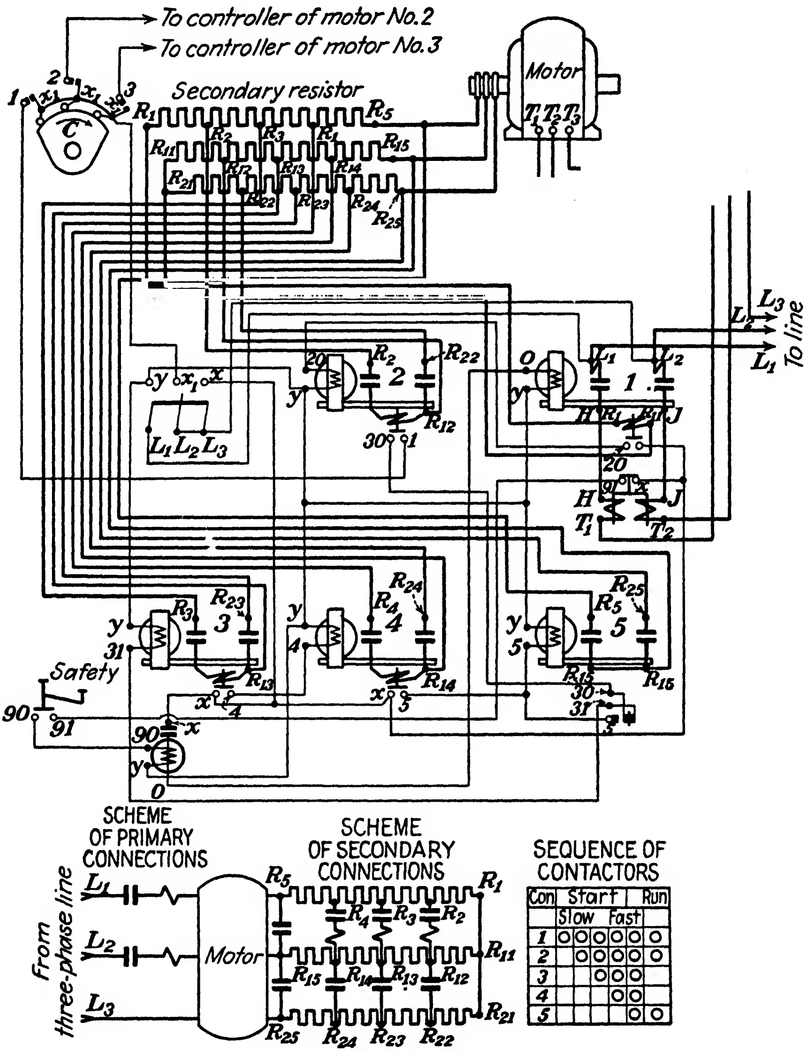


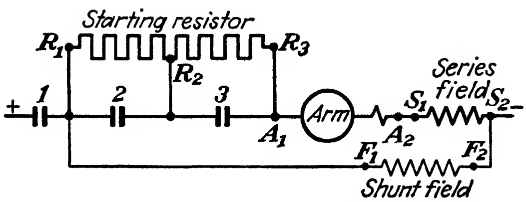
FIG. 119.—Connections of a wound-secondary induction motor for a large elevator pump.

the output of the pump can be materially decreased with only a small loss in the resistance. Assuming a 10 per cent reduction in speed, only 10 per cent of the input of the motor will be wasted as heat in the resistance.

MACHINE TOOLS

Machine tools use either reversing or nonreversing general-purpose starters. Some have a dynamic brake for stopping and, sometimes, a drift point on the controller, to keep the brake circuit open. Typical diagrams are shown in Figs. 121–126.

FIG. 120. Westinghouse drum controller for machine-tool service.

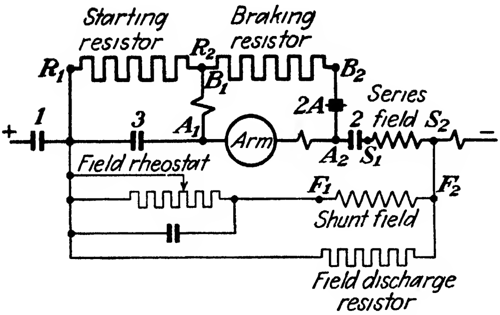


Con	Run		
1	O	O	O
2		O	O
3			O

FIG. 121.—Connections of nonreversing machine-tool controller panel.

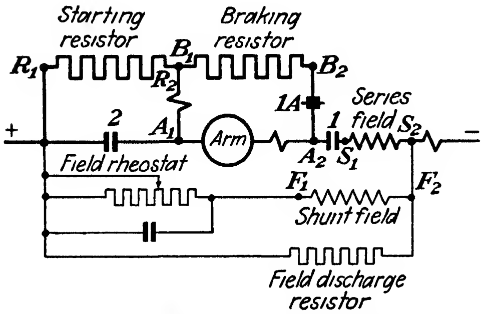
PRINTING PRESS

A printing press requires a very slow speed for make-up and for feeding the paper through the press. One method for getting this slow speed is to use a small motor for operation during the make-up period. The diagrams show a simple type of this control (see Figs. 127 and 128).



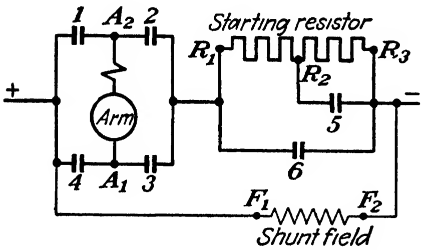
Con	Off	Dft	Start		Run
1			O	O	O
2		O	O	O	O
3				O	O
2A	O				

FIG. 122.—Connections of nonreversing machine-tool panel with a dynamic brake.



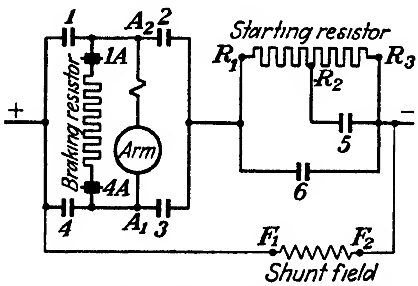
Con	Off	Start		Run
1		O	O	O
2			O	O
1A	O			

FIG 123.—Nonreversing machine-tool controller with the addition of a drift-point contactor



Con	For			Off	Rev		
1	O	O	O				
2					O	O	O
3	O	O	O				
4					O	O	O
5	O	O				O	O
6	O						O

FIG 124.—Connections of a reversing-control panel



Con	Rev Start			Off Bk	For Start		
1					O	O	O
2	O	O	O				
3					O	O	O
4	O	O	O				
5	O	O				O	O
6	O						O
1A	O	O	O	O			
4A				O	O	O	O

FIG. 125—Connections of reversing-control panel with a dynamic brake.

MINE LOCOMOTIVES

Mine locomotives may be operated by storage batteries. The diagram in Fig. 129 shows a typical control scheme for two series motors.

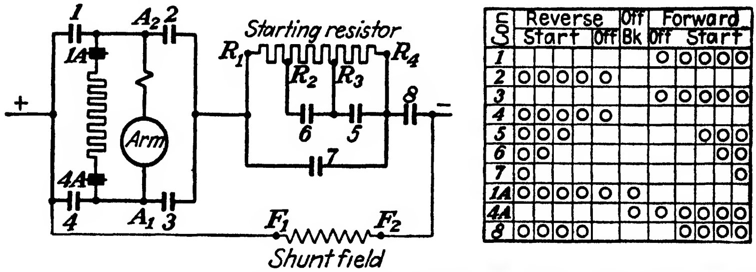


FIG. 126.—Connections of a reversing-control panel with addition of drift-point contactor.

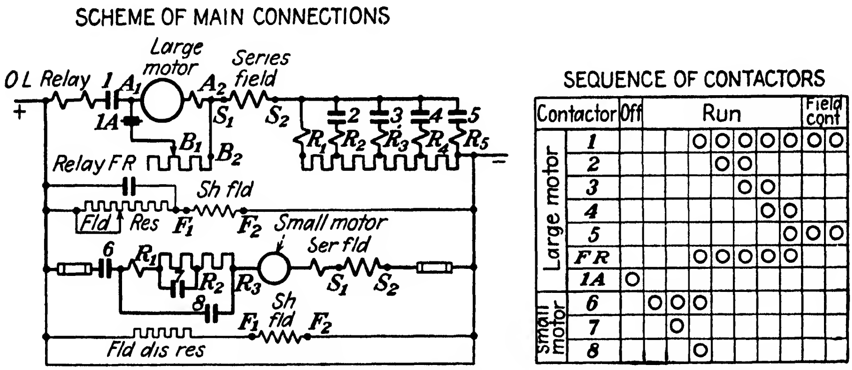


FIG. 127.—Printing-press control for operation over a wide range of speeds.

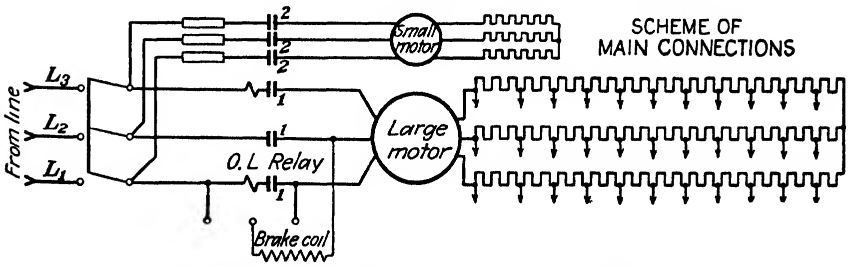


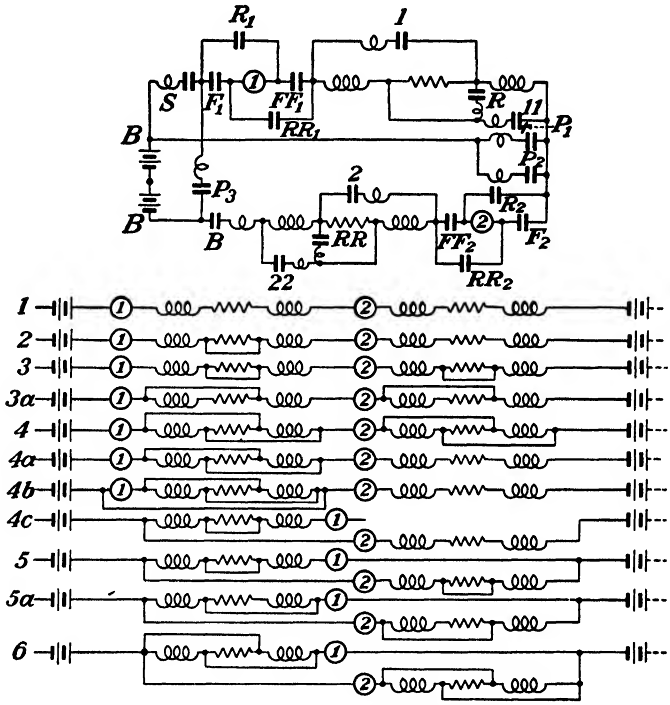
FIG. 128.—Printing-press control for a.c. motors.

Trucks and other vehicles operated by storage batteries use similar control. Control for single motors is much simpler.

OTHER SPECIAL CONTROL EQUIPMENT

Water Rheostats.—A water rheostat of any kind is a special-purpose controller. Although it is usually not very popular, it has some very

desirable features. These rheostats differ so widely in design that no attempt has been made to cover them extensively in this book. Figures 158, 159, and 245 illustrate two types.



SEQUENCE OF CONTACTORS

Step	Main drum											Reverse drum							
												Forward				Reverse			
	S	B	R	R	1	11	2	22	P_1	P_2	P_3	F_1	FF_1	F_2	FF_2	R_1	RR_1	R_2	RR_2
1	O	O										O	O	O	O				
2	O	O	O									O	O	O	O				
3	O	O	O	O								O	O	O	O				
3a	O	O	O	O	O		O					O	O	O	O				
3b	O	O			O		O					O	O	O	O				
4	O	O			O	O	O	O				O	O	O	O				
4a	O	O			O	O						O	O	O	O				
4b	O	O			O	O			O	O		O	O	O	O				
4c		O	O						O	O		O	O	O	O				
5		O	O	O					O	O	O	O	O	O	O				
5a		O	O	O	O		O		O	O	O	O	O	O	O				
5b		O			O		O		O	O	O	O	O	O	O				
6		O			O	O	O	O	O	O	O	O	O	O	O				

FIG. 129.—A two-motor storage-battery control for a locomotive.

The water rheostats will carry heavy overloads, because the heat is absorbed by vaporizing some of the water. They are used for field testing and emergency repairs because they can be constructed quickly from water barrels or other available tanks, using iron plates for elec-

trodes. The following information may be useful in approximating the size of a temporary rheostat.

The current density on the plates or electrodes should not exceed 5 amp. per sq. in. of surface. Higher values will cause vapor bubbles to form on the electrodes, reducing their effective area and causing steam-

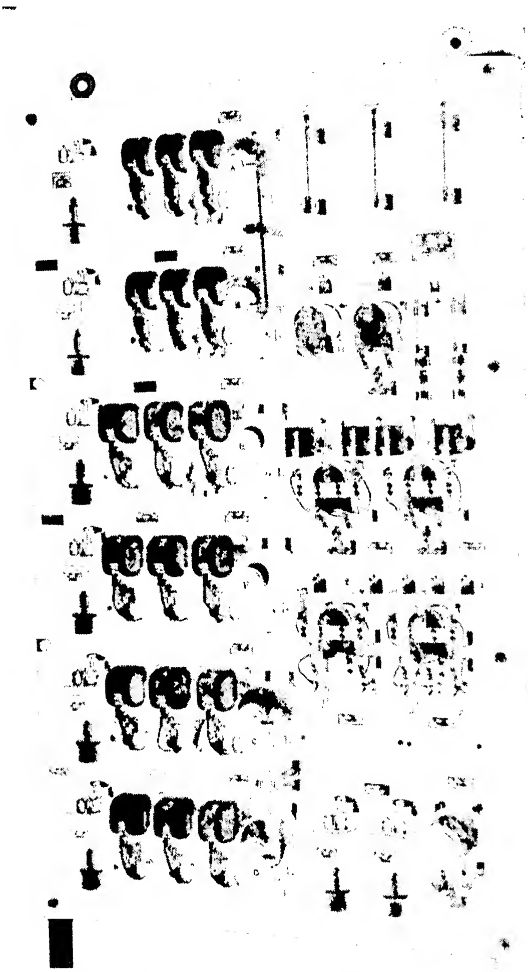


FIG. 130 —Cutler-Hammer control panel for a d c steel-mill motor.

ing; then the current will fluctuate Provide 1-in. separation of plates for each 100 volts between plates The resistance will depend upon the density of the solution.

The electrolyte is made of a solution of sodium carbonate (Na_2CO_3), using as pure water as is obtainable. Sodium carbonate is obtainable

commercially in two forms, sal soda and soda ash, the difference between these two being in the amount of water of crystallization that they

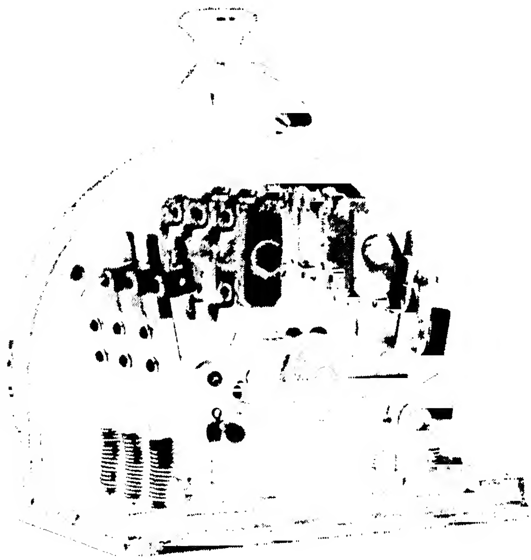


FIG. 131.—General Electric cam-operated master switch for steel-mill service.

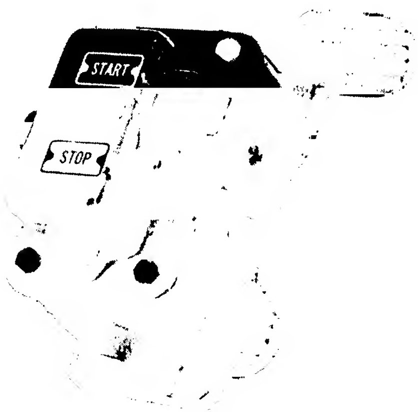


FIG. 132.—General Electric treadle-operated watertight push button.

contain. Sal soda contains approximately 35 per cent to 40 per cent of sodium carbonate (Na_2CO_3) while soda ash contains from 95 per cent to 99 per cent of Na_2CO_3.

Add ½ to 1 lb. soda ash to 100 lb. water. If it is found that the current should be larger, more soda should be added. After a 3 per cent solution of sodium carbonate is obtained, further addition of this material will only slightly affect the resistance. The largest variations of resistance are obtained between 0 and 1 per cent solution.

The operating temperature of the electrolyte should not exceed 160°F. It may be necessary to provide cooling coils to keep the temperature down; 5 to 6 gal. per hp. hr. absorbed by the electrolite will probably

FIG. 133.—Track-limit switch built by the Clark Controller Company. The contacts are double break, silver to silver. They can be changed from normally open to normally closed and either single or double pole can be used. The operating arms are malleable iron, cadmium plated, and by means of a holding bolt may be adjusted with respect to the shaft in any required position for operation.

be enough. The horsepower-hours can be determined from the complete load cycle by the following formula:

HP = horsepower of motor.
a = full-load torque.
b = starting torque.
c = starting time in minutes.
d = number of starts per hour.
e = regulating torque or torque when running at reduced speed.
f = per cent speed reduction.
g = number of minutes per hour during which speed regulation is required.

Then the horsepower-hours absorbed equals

$$\left(\frac{HP}{2} \times \frac{b}{a} \times \frac{c}{60} \times \frac{d}{1}\right) + \left(\frac{HP}{1} \times \frac{e}{a} \times \frac{f}{100} \times \frac{g}{100}\right)$$

Auxiliary Switches.—Such auxiliary switches as over-speed switches, limit switches, friction switches, bearing thermostats, and many others

which are available, are necessary for some applications. They open the control circuit usually to guard against accident. Details are to be found in commercial publications.

A number of special applications of motor drive are given in some detail in "Electric Motors in Industry," by D. R. Shoults and C. J. Rife.[1] The principal electric manufacturers have special publications covering electric power in different industries.

Control equipment is so flexible that it can be applied to any motor drive when the operating conditions are definitely known. Experience is continually improving the automatic features of these special controllers.

[1] SHOULTS, D. R., and C. J. RIFE, "Electric Motors in Industry," Chaps. IX–XI, John Wiley & Sons, Inc., New York.

CHAPTER IX

MECHANICAL AND DYNAMIC BRAKING

The previous chapters have dealt with methods of accelerating the motor from rest to full speed. In this chapter we shall discuss means of stopping the motor, commonly called "braking." The two general methods employed are (1) friction braking and (2) dynamic braking.

FRICTION BRAKING

The Magnet Brake.—The type of friction brake usually employed for electric motors is known as a "magnet brake." It consists of a friction

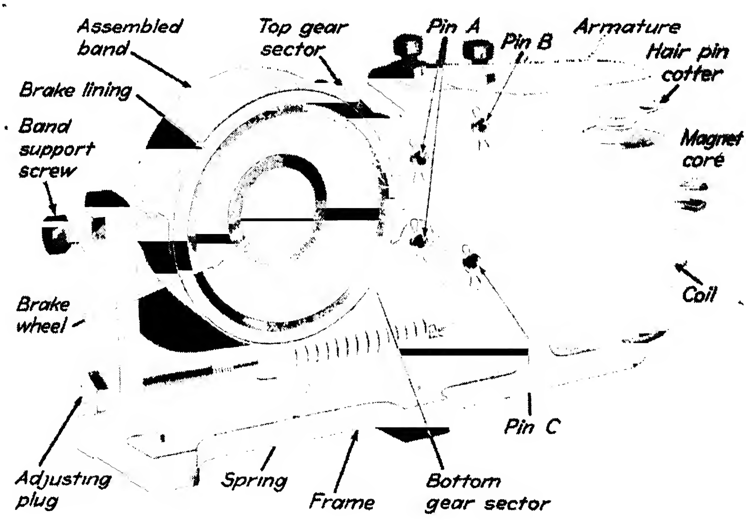


Fig. 134.—Clark Controller Company's band brake. Direct current magnet release; spring applied

member held against the brake wheel by a spring or a weight and released by a magnet. The various commercial designs of this brake are shown in Figs. 134, 136–137, and 139–141. The releasing magnet may be designed for either direct current or alternating current. The a.c. magnets are always shunt wound. The d.c. magnets may be series, shunt, or compound wound, depending on the application. Most d.c. magnet brakes are wound with series coils. The heating characteristics of these coils should be the same as the series coils of the motor with which they

are used. The most common applications for these series-wound brakes are cranes and hoists. The coil is connected in series with the motor armature and releases the brake shoes as soon as current is supplied to the motor. The shunt-wound brake is applied to elevators and a few other applications where the load on the motor varies over a wide range.

The a.c. magnet brake is always provided with a shunt coil. This coil may be connected across two of the primary circuits of a wound-secondary induction motor so that it will release whenever the motor primary is energized. This arrangement cannot be applied to squirrel-

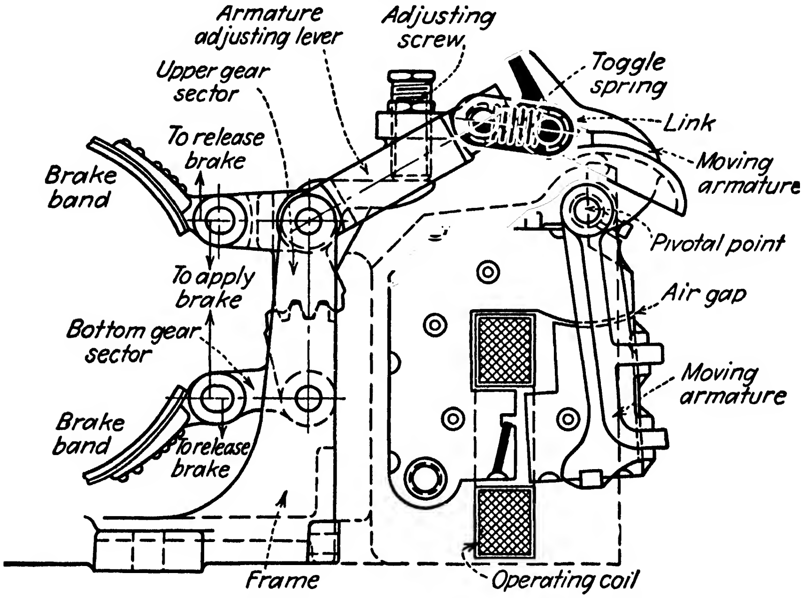


FIG. 135.—Alternating current magnet for releasing brake Fig. 134.

cage motors if reduced voltage is used in starting. In this case, a separate switch is required for the brake coil.

A mathematical discussion of the stored energy of a rotating body such as a motor armature or a moving load such as a hoist can be found in any textbook of mechanics.[1]

The design of a magnet brake may seem to be a simple one. In practice it has been found difficult to make a brake embodying all the desirable features. A brief discussion of some of the elements entering into this design will be of interest.

The Brake Shoes.—Experience has shown that the shoe type of brake is the design best adapted for general applications. The brake shoes are

[1] A concise explanation of these formulas is given by E. M. Bouton in his article on the braking of electric motors, *Elec. J.*, May, 1918, p. 168.

provided with a lining that can be renewed from time to time. This lining should have a constant coefficient of friction over a wide range of speed and should not be affected by moisture or by a small amount of oil that might get on the brake wheel. This lining should be a good conductor of heat and the coefficient of friction should not be seriously affected by any operating temperature. The best form of brake lining now available consists of asbestos and rubber interwoven with copper wires. This lining is usually riveted to a cast-iron shoe, the whole shoe being removable in order that the lining may be replaced.

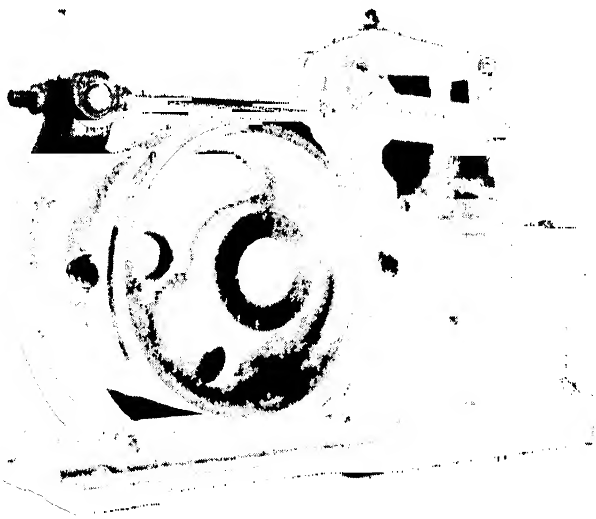


Fig 136 Westinghouse shoe type of magnet brake

The Brake Wheel—The diameter of the brake wheel should be kept small in order to reduce its stored energy and to keep the fiber stresses in the rim within safe limits The stored energy represents a direct loss, as the brake must absorb this energy in addition to stopping the motor armature and load. The outer fiber stress enters as a factor in wheels of large diameter and in some cases makes it necessary to use steel wheels. The series motors with which these brakes are used are guaranteed to operate at a speed considerably above normal without mechanical injury to the armature. The brakes used with these motors must have the wheels so designed that there will be no danger of bursting when they are operating at the maximum guaranteed speed of the motor.

Another limitation in the size of the brake wheel is the distance between the motor shaft and the motor feet. When they are separately mounted, it is desirable to have the brake wheel small enough to permit

mounting the brake on the same foundation level as the motor. Brakes that are attached to the motor should have their mechanical parts designed so that they will clear this foundation line.

These limitations fix the maximum diameter and weight of the brake wheel. On the other hand, the larger the diameter of the brake wheel, the greater the torque exerted with a given pull on the magnet. The torque of a brake is equal to the force exerted by the brake shoes multiplied by the radius of the wheel. Its value is usually expressed in foot-pounds, the diameter of the wheel being given in feet. The force exerted by the brake shoes is equal to the area of the shoe times the pressure per square inch permissible with a given lining. If we select a working pressure per square inch with a brake-shoe lining that will give reasonable wear,

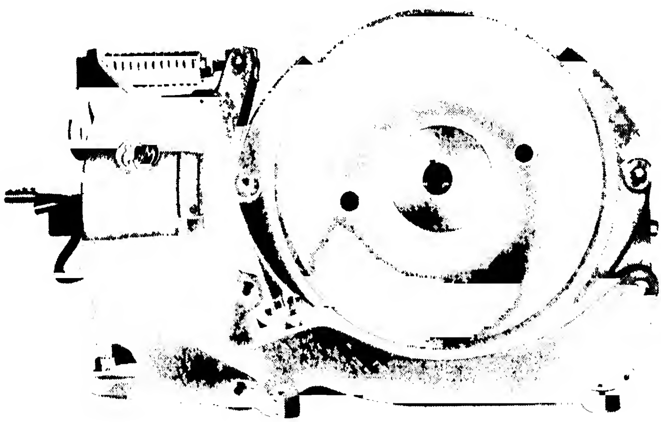


Fig. 137.—Electric Controller and Manufacturing Company's d c magnet shoe brake.

and have determined the maximum diameter of wheel that can be used, we can then obtain the width of the shoe. It is found in practice that the percentage of brake-wheel surface covered by the shoe remains constant and that the width of the brake shoe may be assumed to have a definite relation to the diameter of the wheel. Assuming a definite ratio for these values and a fixed working pressure per square inch for the lining, we obtain the curve shown in Fig. 138 which gives the relation between the torque and the brake-wheel diameter corresponding to these design limitations.

Adjustment for Wear.—As the brake lining wears down, means should be provided for adjusting the shoes so that the clearance between the brake wheel and the shoes is kept within small limits, in order that the magnet may release them. This adjustment should be so arranged that, if neglected, the brake shoes will always set firmly against the wheel and

the gap between the armature and the core of the magnet will be gradually increased. If this continues without attention, in time the magnet will fail to release the brake. This condition will be apparent in the operation of the equipment and will, therefore, get attention. In no case should the design of the brake be such that the brake shoe will fail to set against the wheel.

The Magnet.—Two types of magnets are available for brakes, the armature type and the plunger type. Theoretically, the plunger type is

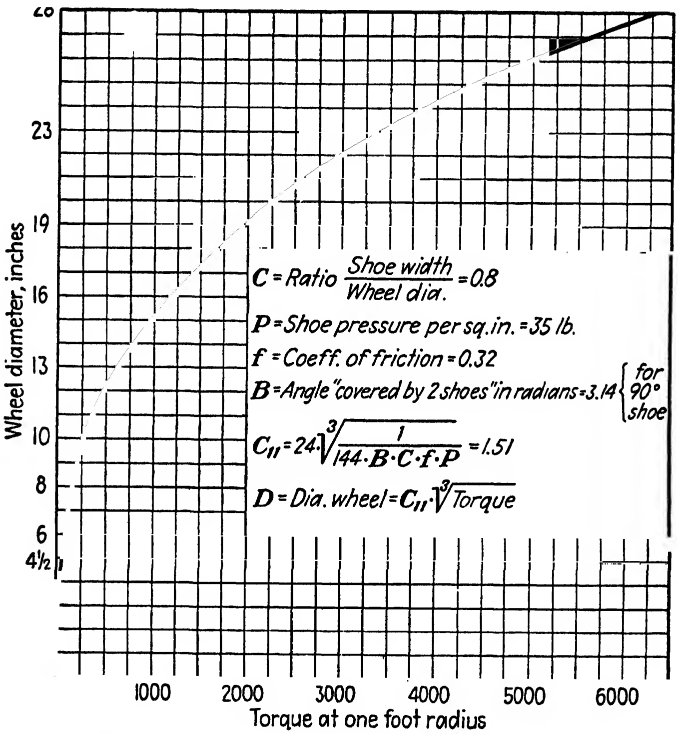


FIG. 138.—The relationship between the torque and the wheel diameter.

the more efficient, but the selection of the type of magnet depends upon the general design of the brake and its application.

Magnet coils can now be impregnated and treated to make them moisture resisting to a very high degree, so that an open coil is satisfactory for most installations. Where this coil is exposed directly to the weather or is intended for use on shipboard, a totally enclosed magnet should be used.

The size of the magnet is determined by the pull required to release the brake shoes with the maximum air gap in the magnetic circuit. At this point most of the ampere turns are used to overcome the reluctance

in the air gap, so that the iron used for d.c. magnet frames can be selected on the basis of its cost rather than on that of its magnetic properties. Care should be taken in the design of the magnetic circuit to reduce the leakage paths to a minimum, and to prevent the iron core from becoming saturated, which reduces the pull.

A magnet should be large enough to release the brake shoes quickly. When it is series wound, the brake coil is usually designed to release the magnet at 40 per cent of the rated load of the motor and to hold the magnet in the closed position as low as 10 per cent of the rated load of the motor. Series windings on d.c. magnets have the following several advantages:

FIG. 139.—Cutler-Hammer vertically mounted magnet brake

1 They can be connected in series with the motor armature, reducing complications in wiring.

2 The coils have low inductance and, therefore, act quickly.

3 Should the series motor overspeed, it will reduce the current to a low value and allow the brake magnet to set, thus reducing the liability of a runaway

4. In case the armature circuit of the motor should be accidentally opened, the brake will set This is of particular advantage in lowering loads

5 The voltage between turns is so low that an insulation breakdown seldom occurs and insulating material can be used having high heat-resisting qualities.

When a shunt winding is required for a d.c. brake, it is advisable to design this winding for a relatively low voltage and use a resistance in series with it. In most cases a shunt resistance will also be required to take the discharge. The fewer the turns on a shunt coil, the more quickly it will act.

The a.c. magnet presents some additional problems. The iron structure must be laminated to prevent eddy-current loss and the pole face must be provided with shading coils to reduce the noise and eliminate vibration. The a.c. flux passes through zero twice every cycle; therefore, the magnetism will also pass through zero the same number of times. In order to prevent the magnet armature from releasing each time the current passes through zero, shading coils, consisting of a copper or brass strap, are placed around a portion of each pole face. These

coils cause the magnetic flux in the area surrounded by the coil to lag behind the flux in the other part of the circuit, so that there is always sufficient flux to hold the armature firmly against the pole face (Fig. 135).

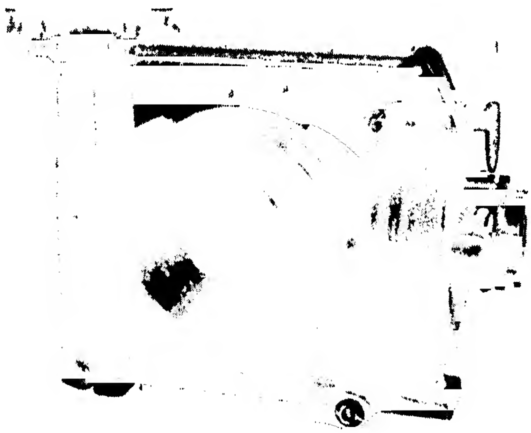


Fig. 140 Cutler-Hammer horizontally mounted magnet brake.

Alternating-current brake magnets of the smaller sizes are wound single phase, but the larger sizes are sometimes wound polyphase. The current taken by the magnet with the armature gap open is considerable,

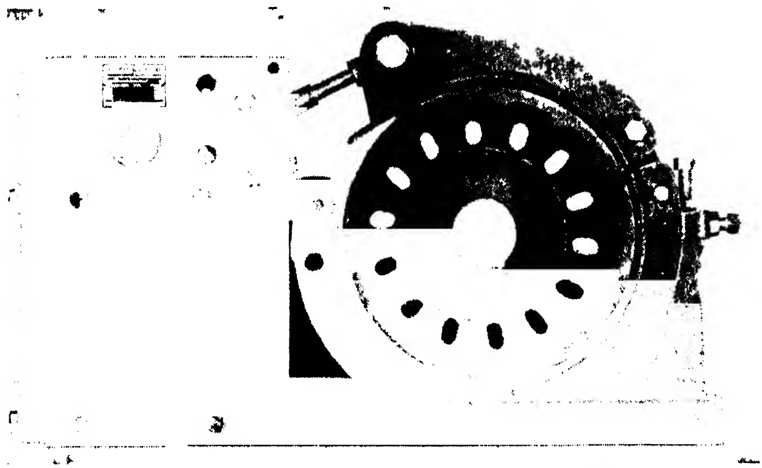


Fig. 141 —General Electric three-shoe magnet brake.

and it may be desirable to use a polyphase winding to distribute the load between the phases when larger sized magnets are used.

Mechanical Parts —The brake structure supporting the magnet and the shoes is very frequently made of cast steel in order to give it the proper

strength. Stresses set up on portions of this structure are quite severe and are suddenly applied, so that care must be taken in the design of the parts. When the brake magnet releases the armature, a spring or weight forces the shoes against the brake wheel. The shoes travel only a very short distance, but some of the brake levers have more travel and store up considerable energy. This kinetic energy increases the pressure of the brake shoes against the wheel and may cause the brake shoes to exert enough torque to twist off the motor shaft. In order to avoid this, the brake lever attached to the magnet armature or core is usually arranged with a lost motion, so that it can overtravel without exerting pressure against the brake shoes. Springs are preferable for applying the brake shoes as they have little inertia. Where a weight is used, it should have a dashpot to control its action or some form of spring should be used to cushion the blow.

The size of the magnet is fixed by the pull required and the air gap through which the armature travels. In order to keep the design of these magnets down to a reasonable size, the brake shoes are given very little clearance when they are released. The magnet structure must therefore be very rigid so that there is little or no deflection in these parts; otherwise, the magnet does work in deflecting these parts before it releases the shoes, and the design is very inefficient.

DYNAMIC BRAKING

If a motor is driven by the load and its field remains excited, it will generate a voltage which, if high enough, will return energy to the line. The motor in this case becomes a generator and does work in holding the load. Such an arrangement is useful only where the motor is driven at a high speed. If it is desired to stop the motor, this generator action can be used by connecting a resistor across the motor terminals, reducing it gradually, if necessary, to bring the motor to rest. This method of stopping a motor is known as "dynamic braking." It is used very extensively for hoists and other moving loads that must be frequently stopped. The extra duty of generating the braking current increases the heating in the motor armature and must be taken into account in selecting the motor. This method does not use friction surfaces and there are therefore no parts to wear out. It is very useful in reducing the speed of the motor to a low value, so that a friction brake is required only to stop the motor from the low speed and to hold the load stationary.

When a field rheostat is used to adjust the motor speed, it can be short-circuited during dynamic braking, to build up the field strength while the armature is slowing down and maintain the braking current at a higher value. This brings the motor to a slower speed before the friction brake is applied. The dynamic brake resistor across the arma-

ture, if desirable, can be provided with taps and means for short-circuiting it in steps, to maintain the braking current at a high value. The control is the reverse of acceleration.

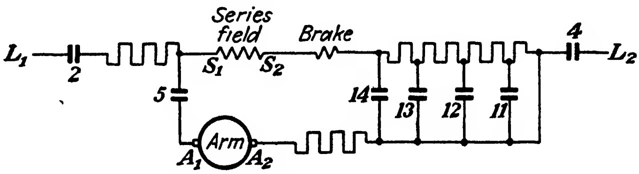


FIG. 142.—Crane controller diagram showing dynamic-brake lowering of load with a series motor.

A series motor can be connected so that it operates as a shunt generator in lowering loads on hoists and for other similar applications. Figure 142 shows one method of doing this. The motor is started in the down direction as a shunt motor with an armature-series resistor and a

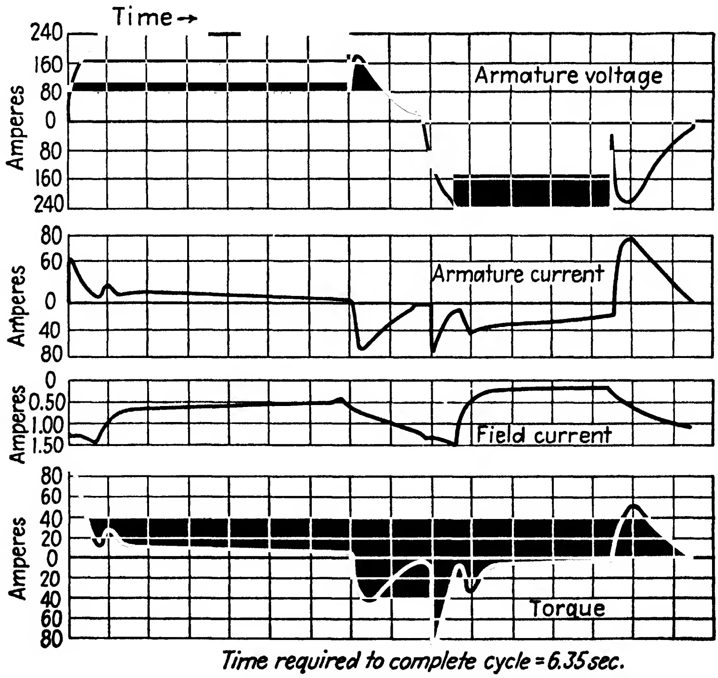


FIG. 143.—Dynamic braking of a 4:1 adjustable-speed d.c. motor.

resistor in series with the field connecting it across the line. When the load overhauls, the motor becomes a shunt generator and can have its speed increased by inserting resistance in the circuit. No. 14 is first opened to increase speed; then Nos. 13, 12, and 11 open in succession, to give further speed increase. When there is no load on the hook, the

motor again operates as a shunt motor to lower the hook. This has been more fully explained under the subject of crane control in Chap. VIII.

An interesting application of dynamic braking is illustrated in Fig. 143, in connection with an adjustable-speed d.c. motor. This motor has a 4 to 1 adjustable-speed range and very little energy is required to stop it from the low-speed position. When it is operating at a higher speed, the motor field is connected for its maximum value at the time the dynamic-brake circuit is established. This causes the motor field to build up while the armature speed is being reduced. At first this increases the voltage of the motor terminals, causing an increased dynamic braking torque. As the speed is further reduced, this voltage decreases rapidly. A relatively quick stop results without changing the value of the dynamic-brake resistance.

Dynamic braking should be used whenever it is necessary to stop the motor quickly. It is more economical than a friction brake and requires less attention.

Plugging.—When a motor is running in one direction and is quickly reversed, the action is termed "plugging." It is usually done to stop the motor quickly. The control should be designed for this action, to prevent damage to the motor or to driven machinery. The effect on the motor is different for d.c. shunt and series motors and for a.c. induction motors. The field flux of the d.c. shunt motor remains substantially constant and its counter e.m.f. is added to the line voltage when the armature connections are reversed. Additional armature resistance is added to the starting resistance to limit the current to the same value as it had at starting. This means adding about 85 per cent more ohms. The plugging resistor should be automatically short-circuited when the motor is started from rest; this can be done by using a relay responsive to zero armature voltage and in other ways.

The field flux of the d.c. series motor is proportional to the armature current and would increase when the motor is plugged, unless the current was limited by additional resistance. An increase in field flux, if it is permitted, will increase the armature voltage that is added to the line volts and thus increase the current up to the saturation point of the iron in the field circuit. It is, therefore, more important to control the plugging current in a series motor than in a shunt motor. A compound motor might have its series turns oppose the shunt-field turns and thus reduce the plugging current.

The energy required to stop the motor during plugging is usually the mechanical energy stored in the motor armature and the driven load. The plugging resistor can be short-circuited in more than one step if it is desirable to have the motor stop more quickly. Usually the reverse connections exert sufficient torque for this purpose.

Plugging can be prevented with a magnet energized by the armature voltage and arranged to lock the reverse contactors open until the motor is nearly stopped. This is usually done when dynamic braking is used.

The a.c. induction motor performs entirely differently when plugged. Reversing the rotation of the a.c. field gives the secondary double the slip

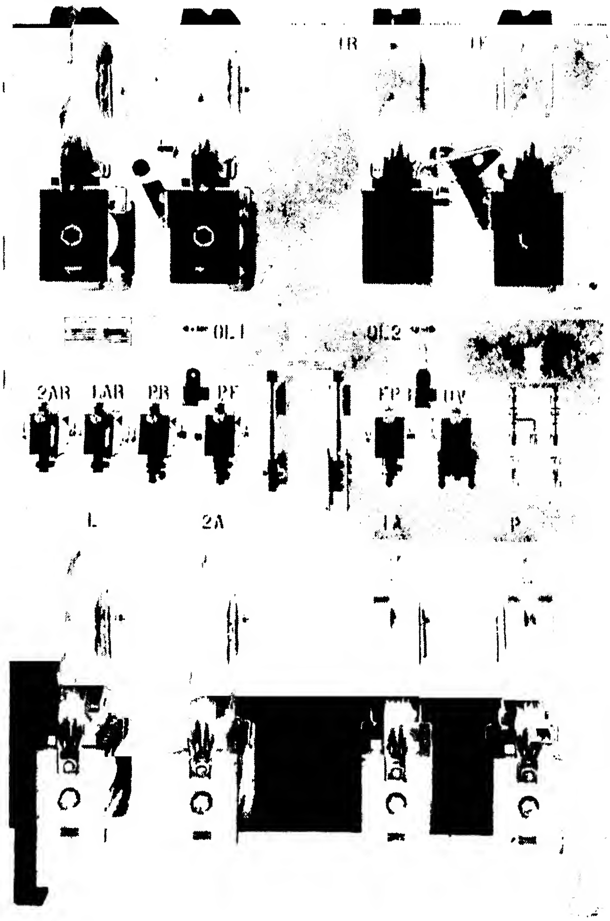


FIG 144 —General Electric reversing and plugging magnet controller for a d c motor.

it had at rest and decreases the torque of a squirrel-cage motor to less than that obtained at starting, unless the secondary has unusually high resistance. The motor-power factor drops and increases the wattless current. The motor can be designed to have a plugging torque low enough to prevent damage to the machine gearing.

When plugging is used only for stopping, automatic means, such as the zero-speed switch, must be provided to open the primary connections when zero speed is reached. The wound-secondary motor can have its secondary resistance adjusted during plugging, to control both the torque and the current. The secondary voltage is almost double, and it should be insulated for this condition.

Applications.—In applying a brake to a motor, advantage can be taken of the friction in the machinery. In starting a load, the motor must overcome both the load torque and the friction in the machinery. In stopping this load, the friction of the machinery assists the brake. To illustrate, let us assume a hoist having 80 per cent efficiency. If the torque required to accelerate the load is represented as 100 per cent, the torque required to stop the load in the same length of time would be represented as 64 per cent. In order to provide a reasonable factor of safety, the friction brakes should be selected having a torque equal to the full-load torque of the motor. This assumption is based on the fact that many motors used on hoists and similar applications exert more than their full-load torque during the accelerating period and therefore the brake should have full-load torque in order to provide a margin of safety.

If a friction brake is used to lower a load any considerable distance, the energy required to maintain a fixed speed must be absorbed by the brake. This means that a great deal of energy will be absorbed by the brake and must be radiated from it. The size of the brake for such an application would be fixed not by the torque but by its ability to radiate energy. Steam hoists that use a lowering brake have a much larger brake than is common to motor applications. A comparison of this kind illustrates the advantages of using dynamic braking for lowering the load and employing a friction brake only for making the final stop and for holding the load. Dynamic braking adds to the average heating load on the motor.

CHAPTER X

REGENERATION

The term "regeneration" is usually applied to a system of motor drive where the load exerts a negative torque and drives the motor as a generator, returning power to the system. It is similar to dynamic braking where the motor delivers power to a resistor, which transforms the energy into heat. A system using regeneration must have sufficient positive load to absorb all the energy delivered, or else a resistor should be arranged to absorb the surplus energy.

When regeneration is used for lowering a load, such as the cage of a hoist or a railroad train going downgrade, the retarding torque will be lost if the circuit is open. It is necessary, therefore, to provide protective devices to hold the load by mechanical braking should the electric circuit become disconnected.

In order to obtain regeneration, the induced voltage of the motor or motors must be in excess of the voltage at which power is delivered, or, to state it in another way, the motors driven as generators will deliver power to the line only if their voltage is in excess of the voltage at which the positive load is operating. Regeneration may be obtained from motors with shunt characteristics by operating them above their normal speed. For instance, an induction motor or a d.c. shunt motor when lowering a load will return power to the line and hold the load at a constant speed slightly in excess of the normal full speed of these motors. Reduced speeds can be obtained by increasing the field strength of a d.c. motor so that the required voltage will still be generated when the motor is operated below the maximum running speed. Several d.c. motors may be connected in series or in parallel combinations; or, in the case of an induction motor, the number of poles may be changed.

The regenerative system must provide for inherent current regulation so that the machines will quickly adapt themselves to any sudden drop in line voltage. This is usually taken care of by automatically changing the field strength of the motors. The line voltage may change too quickly to permit control apparatus to insert armature resistance to protect the motor.

Regeneration may be used to maintain the load at the maximum operating speed, or it may be used to reduce the speed so that part of the energy stored in the moving load will be returned to the line. The

stored energy is proportional to the square of the speed, so that a reduction in speed to one-half of the maximum would mean absorbing three-fourths of the stored energy. If the speed is reduced to 20 per cent of the maximum before the final stop is made with friction brakes, only 4 per cent of the stored energy will be wasted.

There are many examples of regeneration with shunt d.c. motors or induction motors, such as hoists, elevators, etc. A notable example is that of freight locomotives using induction motors and regenerating when taking a train downgrade. The inherent characteristic of these motors is such that regeneration is obtained with little or no additional complication.

Where it is desirable to make a material reduction in the speed by means of regeneration, additional features are necessary in designing the equipment. There are a number of different schemes for obtaining regeneration, but for purposes of simplicity they will be grouped under two main headings: (1) field control and (2) voltage control.

FIELD CONTROL

In its simplest form, this control consists of a d.c. shunt motor controlled by varying the strength of the shunt field. This is illustrated diagrammatically in Fig. 145. Commercial motors of this type can be obtained with a speed range of 4 to 1. Such a motor can have its speed on regeneration varied in approximately this ratio. When it is operating at its maximum speed on a weak field, the field can be strengthened so that approximately 80 per cent of the stored energy of the load is returned to the line.

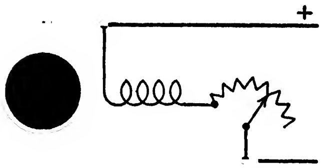


FIG. 145.—Field-control regeneration—scheme 1.

Modifications of this scheme are shown in Figs. 146 and 147. In Fig. 146 the field is excited from a storage battery, and is therefore independent of the line voltage. Figure 147 shows the field energized from an

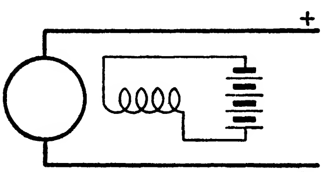


FIG. 146.—Field-control regeneration—scheme 2.

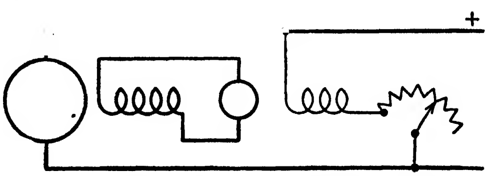


FIG. 147.—Field-control regeneration—scheme 3.

exciter. The field of the exciter is connected to the line and is, therefore, affected by variations in line voltage. If the exciter were self-excited, it would be independent of the line voltage, provided that it were

maintained at a uniform speed. This exciter may be operated by a motor connected to the line with shunt, series, or compound winding, or it may be driven by the main motor through suitable gearing. If it is located on a vehicle, it may be driven by one of the axles. When schemes of control are shown involving an exciter, it will be assumed that the exciter may be driven by any one of the above methods. Each arrangement has its advantages; the method used must be selected for the particular application. If all the various schemes for regenerative

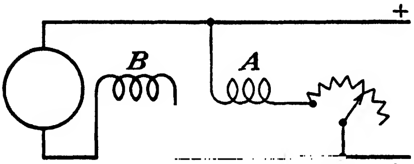


FIG. 148.—Field-control regeneration—scheme 4.

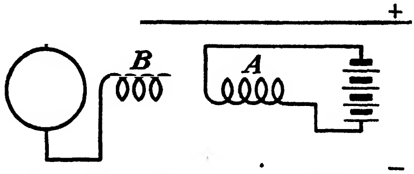


FIG. 149.—Field-control regeneration—scheme 5.

control were shown, together with the various methods of driving the exciter, the subject matter would be complicated and difficult to follow.

The scheme shown in Fig. 145 is limited to a shunt motor. In the scheme in Fig. 146 or Fig. 147, the motor may be either shunt or series.

The three schemes just considered do not provide means for inherent regulation to protect the motor from overloads caused by a sudden drop in line voltage. Figure 148 is the same as Fig. 145, with the exception that the motor has a double winding, the series winding B opposing the shunt winding A and weakening the field strength on overloads. A drop

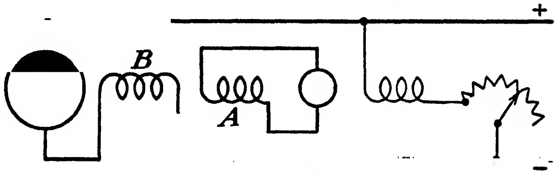


FIG. 150.—Field-control regeneration—scheme 6.

in the line voltage will increase the motor current, and the strength of the compound winding, which opposes the shunt winding, will cause a reduction in the field strength, which in turn reduces the e.m.f. of the motor and maintains the current at a normal value. This regulating action, while inherently in the proper direction, will ordinarily be too slow, on account of the inductive effect of the shunt-field winding.

The field A may be energized from a storage battery, Fig. 149, or from a separate exciter, Fig. 150. If it is energized from a storage battery, the windings may be either shunt or series. If it is series-wound, the inductive effect is relatively small and the regulating char-

acteristics will change the field strength fast enough to prevent abnormal rises in current. The use of the battery makes the field strength independent of the line voltage. The arrangement of Fig. 150 is usually applied to a series motor and is dependent upon the line voltage, the fields of the exciter in this case being connected across the line. If these fields were self-excited, a different set of characteristics would be obtained. Where the field strength is affected by the line voltage, as in Figs. 148 and 150, a drop in line voltage tends to reduce the field strength

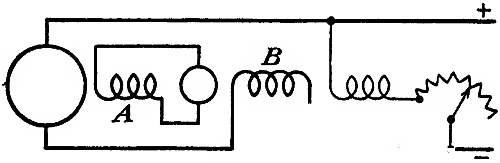


FIG. 151.—Field-control regeneration - scheme 7.

in itself, in addition to the action of the differential compound winding *B*. The arrangement in Fig. 149 depends entirely upon the differential winding *B* for its inherent regulation.

It is desirable to make the main motor as simple as possible and not to interfere with its use in motoring. For this reason, it is better to put the compound winding on the fields of the exciter than on the main motor. The arrangement shown in Fig. 151 is similar to that in Fig. 150, the difference being that the compound winding *B*, which decreases the motor-field strength on overloads, is on the exciter field and not on the motor field.

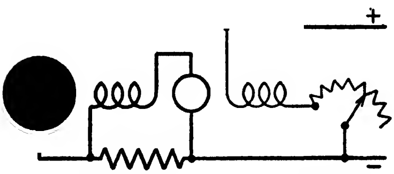


FIG. 152.—Field-control regeneration—scheme 8.

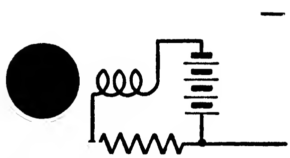


FIG. 153.—Field-control regeneration—scheme 9.

Other arrangements for limiting the current when a decrease in line voltage takes place are shown in Figs. 152 and 153. The main motor field is connected in series with the exciter and in shunt with a small amount of resistance. The voltage on the field is equal to the voltage of the exciter minus the voltage drop caused by the current flowing through the series resistor. If the line current increases, the drop through this resistor also increases, and, assuming that the exciter voltage remains constant, the voltage on the field will decrease in proportion to the increase in line current. Figure 152 shows an exciter with its field connected to the line. Figure 153 has a battery substituted for the

exciter. The arrangement in Fig. 152 is affected by changes in line voltage, whereas the excitation in Fig. 153 is independent of the line voltage. The arrangement shown in Fig. 152 has been used very successfully on large locomotives; it responds quickly to the changes in current caused by fluctuation in the line voltage. The use of a resistance in series with the motor armature also acts as a buffer, although the value of this resistance is very low and the losses represent only about 1 per cent of the losses in the motor.

The schemes that provide for automatic regulation of the armature current with fluctuations in line voltage not only operate to hold the current down to a safe value when the line voltage decreases, but they tend to maintain the line current close to the required value of an increase in line voltage. The increase in line voltage through the action of the compound winding or series resistance operates to increase the field strength and thus restore the current to its former value.

The speed of the motor on regeneration is adjusted by changing the field strength. Where a battery is used, the number of cells in circuit can be changed. In other cases a rheostat is used in the field of the exciter. When the arrangement shown in Figs. 152 and 153 is used, adjustments can also be made by changing the ohms in the series resistor. Each particular application must be carefully worked out and a selection must be made of the scheme of control that is best adapted for that particular application. After the method of control has been determined, the characteristics of the motor on regeneration can be adjusted by varying the amount of compounding where that form of control is used, or the series resistance in Fig. 152 or 153 may be changed. In addition to these two methods of adjustment, the exciter is capable of a wide degree of adaptation by changing its driving means.

VOLTAGE CONTROL

This method of control may be considered under three subheadings: (1) the motor-generator set, (2) the booster, and (3) the combination of motor-generator set and booster

The Motor-generator Set.—A d.c. shunt-wound generator (see Fig. 154) has its commutator connected directly to the commutator of a d.c. shunt-wound motor. Any standard type of motor may be used to drive the motor-generator set. The motor connected to the load has a constant field strength and a variable voltage impressed on its armature by varying the field strength of the generator. To reverse the motor, the generator fields are reversed.

The control scheme is a well-known method of obtaining regeneration and is explained fully in Chap. XI. The speed range obtained

on regeneration is practically the whole speed range of the motor in either direction of operation.

The Booster.—A d.c. machine may be used as a booster (see Fig. 155) or a bucker in series with the main motor, which usually is a d.c. shunt-wound machine. When it is at rest, the voltage of the booster is approximately that of the supply circuit. As the field strength of the booster

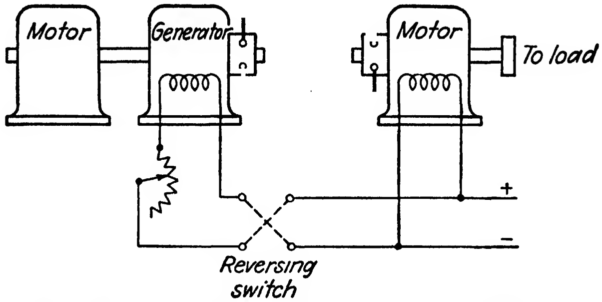


FIG. 154.—Voltage-control regeneration using a motor-generator set.

is decreased, its voltage goes down and the voltage on the motor increases until the motor is operating at line voltage. The fields of the booster may be reversed and gradually increase the voltage on the motor to approximately double the line voltage.

Regeneration with this method may cover the entire speed range of the motor in both directions of operation. The booster may be driven by any form of motor, usually a d.c. shunt-wound machine.

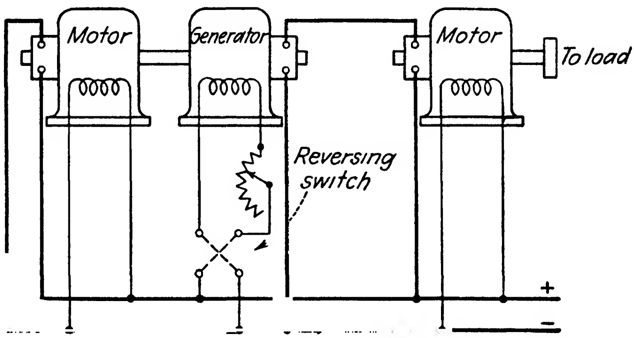


FIG. 155.—Voltage-control regeneration using a booster.

The Motor-generator Set and Booster.—In this arrangement (see Fig. 156) two d.c. shunt-wound machines are coupled together and connected in series across the supply lines. The working motor C is connected across the armature of machine B of this set; its field is shunt wound and has a constant value. The fields of the two d.c. machines forming the motor-generator set are varied inversely to each other.

When the working motor C is at rest, the field of machine A is fully excited and machine B has its minimum field strength, which impresses a low voltage on the motor C. The field of machine A is gradually reduced and that of machine B increased until motor C is accelerated to full speed and the voltage of machine A becomes zero. When regenerating, the voltage of machine A may be reversed so that it will assist machine C in delivering power to the line. The speed reduction during regeneration depends upon the voltage of machine A, and may extend over a wide range. Motor C may have its direction of operation reversed by reversing the connections to its armature.

The schemes shown in Figs. 154 and 155 require the generator or the booster to carry the full motor current all the time, and to deliver full voltage part of the time. These two limitations fix the size of this machine. The arrangement shown in Fig. 156 divides the motor current

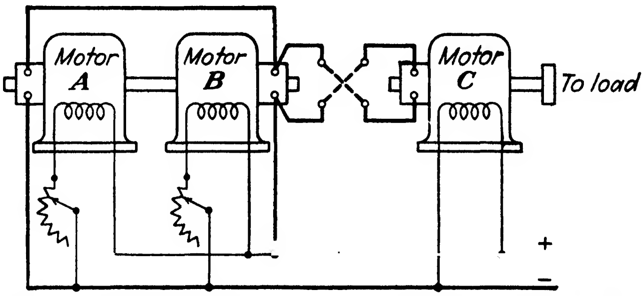


FIG. 156.—Voltage-control regeneration using the combination of motor-generator set and booster.

between machines A and B. When the motor C starts from rest, its total current is supplied by both machines A and B in the inverse ratio of their voltages, the machine B supplying most of the current at slow speeds. This distribution of current permits smaller machines to be used than in the schemes shown in Figs. 154 and 155.

The last two arrangements show the motor and the generator with shunt-field windings only. These machines can be compound wound to obtain better operating characteristics from the motor driving the load. If this motor is operating a hoist, its speed will change with a change in load, owing to the resistance in the armature circuit. This change in speed is known as "regulation." The load may change from the maximum value in the positive direction to a negative load of perhaps 50 per cent of the maximum, so that a considerable change in speed may result. If series windings are used, the motor can be given approximately a flat speed characteristic over the entire range of load.

When it is regenerating, a sudden drop in line voltage may cause an abnormal increase in the regenerating current. This condition can be

taken care of in much the same way as was described under field control. The service conditions will often determine the amount and frequency of voltage disturbances. In railway work, a considerable drop in line voltage must be provided for, while in power work, particularly with the smaller hoists, elevators, etc., the voltage regulation is good. In many cases these motors are operated from the same lines that supply the lighting system. If an induction motor is used for the motor-generator set shown in Fig. 154, the ordinary changes in line voltage will be readily taken care of by the inherent characteristics of the motor. For large installations the induction motor is provided with a slip regulator, which automatically adjusts the current fast enough to protect the motor from damage from voltage fluctuations.

GENERAL

The various forms of field control, with the exception of that shown in Fig. 155, have their widest application in railway work. For the latter it is preferable to use series motors, as they are freer from flashing troubles than are shunt motors. These systems of control require the use of a rheostat for acceleration and speed regulation when motoring. The resistors are also required during regeneration, when the motors are first connected to the line, and also when the motor combinations are changed from parallel to series, etc.

The voltage methods of control have found their principal applications in the industrial field. The scheme illustrated in Fig. 154 is the one commonly used for elevators, large mining hoists, and reversing steel mills. Voltage control does not require a resistor in the armature circuit of the motor. The only rheostats used are in the field circuits, and they consume very little energy. During acceleration and regeneration, the ordinary rheostat losses are eliminated, so that these systems operate very efficiently while the motor is connected to the line. During the time when the working motor is idle, the operation of the motor-generator sets consumes power and represents a direct loss. The control system can be arranged to shut down the motor-generator set during idle periods, to avoid stand-by losses, if sufficient time can be allowed for starting the set before starting the working motor.

CHAPTER XI

VOLTAGE CONTROL FOR DIRECT-CURRENT MOTORS

If a d.c. motor has its field excited at a constant voltage, its speed will be proportional to the voltage impressed on its armature. The methods of obtaining a reduced voltage by means of resistance in series with the armature have already been described. Another method that is little used at present is to provide a source of power, using four or more power wires, the voltage between the different wires being proportioned so that a considerable number of operating voltages can be obtained by connecting the motor armature to different pairs of wires. This method is known as the "multivoltage system." It is objectionable because it requires a number of power wires and special generator equipment, as well. There are also power circuits provided with two outside wires and a central or neutral wire, the voltage between the outside wire being double that between either wire and the neutral. These systems usually have voltages of 115 and 230, respectively, and are used for a limited number of industrial applications.

THE MOTOR-GENERATOR SYSTEM

The increasing size of d.c. motors for planers, hoisting, and the application of motor drive to reversing steel mills, during the last 20 years, has brought into general use a system of voltage control in which a separate generator is provided for each motor. This generator may be driven from any source of power but is usually driven by a constant speed, a.c. motor. The armature of the generator is connected directly to the d.c. motor, as shown in Fig. 157, both machines having their fields supplied from a constant-voltage exciter. The slow speeds of the motor are obtained by reducing the strength of the generator field. If the generator field is reduced to zero and energized in the reverse direction, the rotation of the motor will be reversed. The controller in Fig. 157 shows one means of doing this. The rheostat consists of a closed circuit in the form of a circle. Points *A* and *B* are connected to the + and to the − side of the exciter, and *C* and *D* are connected to the generator field. When the rheostat is in the position shown, the generator field is zero, and consequently the motor speed is zero. If contact 1 is moved to coincide with point *A*, contact 2 with *C*, contact 3 with *B*, and contact 4 with *D*, current will flow from the exciter to *A* through 1 and 2 to *C*,

thence through the generator field to D, and from contact 4 to 3 to B, and thence to the exciter. This will give the maximum field strength to the generator and cause the motor to operate in a forward direction at full speed. Any position between the one shown in the diagram and the one just described will give intermediate values of field strength and

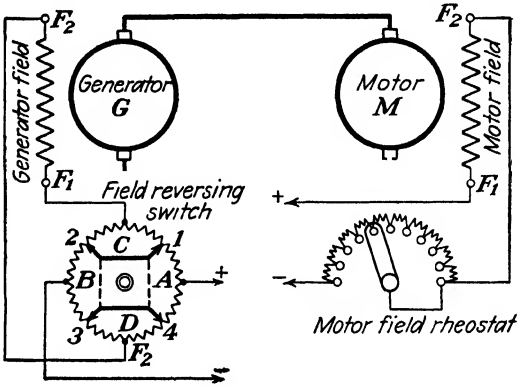


FIG. 157.—Connections for reversing a steel-mill motor.

cause the motor to operate at reduced speeds. If the controller is moved so that contact 1 coincides with point C, contact 4 with point A, etc., current will flow from the exciter to A through contacts 4 and 3 to D, through the generator field to C, through contacts 1 and 2 to B and then to the exciter. This will cause the motor to operate at full speed in the reverse direction. Intermediate positions of the control will give intermediate speeds.

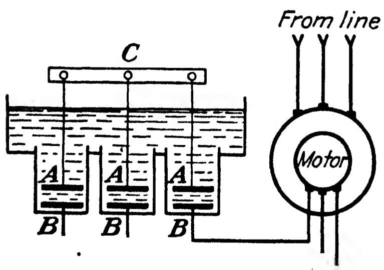


FIG. 158.—Connections of slip regulator to induction motor.

The advantage of such a method of control is obvious. The speed and direction of rotation of the large motor M in Fig. 157 is controlled by switching the small field current of generator G. This current may be in the neighborhood of 100 amp., while the armature current flowing from G to M may be several thousand amperes. This method gives a large number of fixed running speeds and the only losses that occur are the usual losses in the generator and the motor, in addition to the rheostatic losses in the field control.

The speed of motor M may be retarded by reducing the generator voltage to a lower value than the center e.m.f. of the motor. This causes the motor to regenerate and produces dynamic braking. If the generator G is driven by a suitable motor, this method of slowing down will return

Fig 159a —Westinghouse liquid-slip regulator with torque motor for automatic control Figure 159b shows the operating parts of this regulator

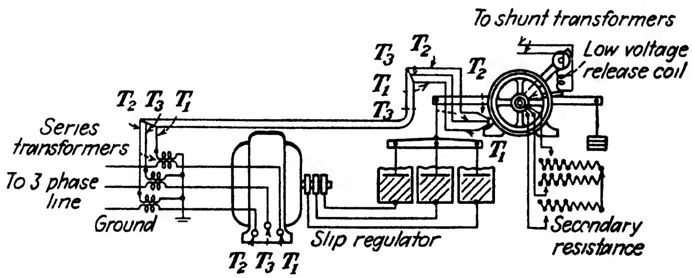


Fig 159b —Diagrammatic view of regulator shown in Fig. 159a.

power to the line. If it is driven by an engine, the generator cannot absorb the power, and the regenerated current must be wasted in a resistance.

The field of motor M can also be varied to increase the speed range of the combination. It is found in practice that the motor M can be arranged for speed control of 1 to 1.5 or 1 to 2 by varying its shunt field, without much additional expense. If less than the full range of operating

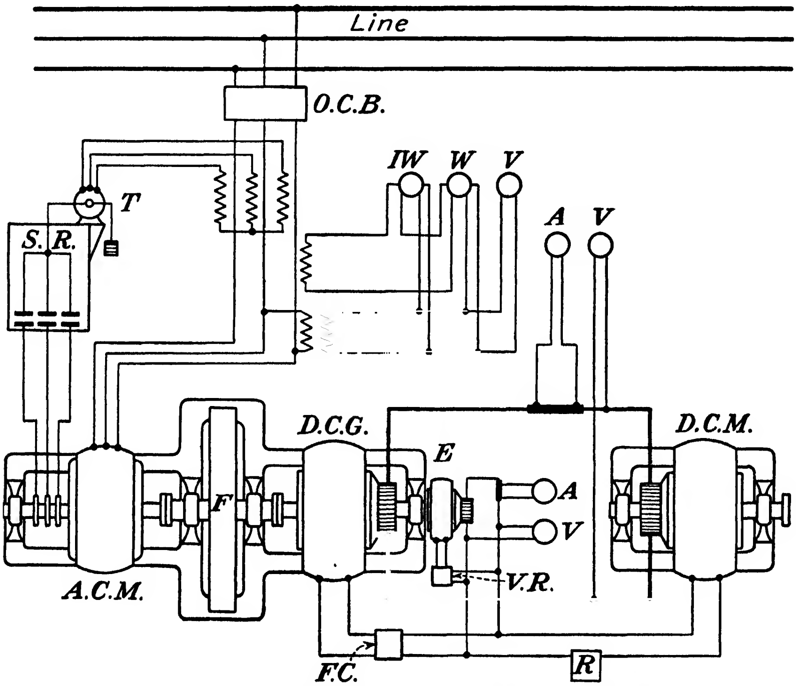


FIG. 160.—Connections of equalizer flywheel hoisting set. *A.C.M.*, wound-secondary induction motor; *F*, flywheel; *D.C.G.*, separately excited d.c. generator; *E*, exciter; *D.C.M.*, separately excited d.c. motor; *S.R.*, automatic liquid slip regulator; *T*, torque motor for slip regulator; *O.C.B.*, oil circuit breaker; *F.C.*, reversing field controller for generator; *R*, rheostat for motor field; *V.R.*, voltage regulator for exciter; *A*, ammeter; *V*, voltmeter; *W*, watt-hour meter; *IW*, integrating wattmeter.

speed is obtained from the generator, a smaller generator can be used. Therefore, the combined field control of the generator and field control of the motor gives cheaper commercial apparatus than would obtaining the entire range of speed control from the generator. This double method of control may seem complicated, but, as it is usually combined in one master switch, very little additional apparatus is required.

Flywheel Power Storage.—When a large generator G is driven by a motor, this method of controlling the operating motor is usually combined with a system for reducing the maximum power demand from the generat-

ing station. The power supplied for large installations is usually alternating current, so the generator G in Fig 157 is driven by an induction motor, shown in Fig 160. On the motor-generator shaft is placed a large flywheel, which is used for storing energy during the low-demand period of the cycle and for supplying energy during the maximum-demand periods. This flywheel performs a similar function to a storage battery floating on the d.c. system. The flywheel gives out energy or absorbs energy, depending upon the speed of the motor-generator set.

The driving motor for this set is provided with a wound secondary and a slip regulator is introduced in its secondary circuit If the resistance in this secondary circuit is varied automatically with the load, the

Fig 161 —Equalizer flywheel hoisting set showing automatic liquid slip regulator

motor will take an approximately constant amount of power from the line This is desirable only above full load on the motor. If the demand for power is in excess of this load, the slip regulator introduces more resistance in the motor secondary and allows the motor-generator set to slow down, so that the flywheel can supply this excess of power. When the demand on the generator is less than normal, the resistance in the secondary of the induction motor is decreased and the excess power input is used in accelerating the flywheel, thus storing up mechanical energy to be given out later when an excess demand occurs.

A diagram combining the control of the motor-generator set with the control of the operating motor is shown in Fig. 160. This diagram is merely a scheme of connections intended to illustrate the principle, and does not show any of the control apparatus in detail. The slip regulator

in the secondary of the induction motor consists of three fixed electrodes marked *B* in Fig. 158. Each of these electrodes is insulated and connected to one of the slip rings of the induction motor. Above them in the liquid are suspended three electrodes marked *A*, attached to a common support *C*, and electrically connected through this support. The liquid

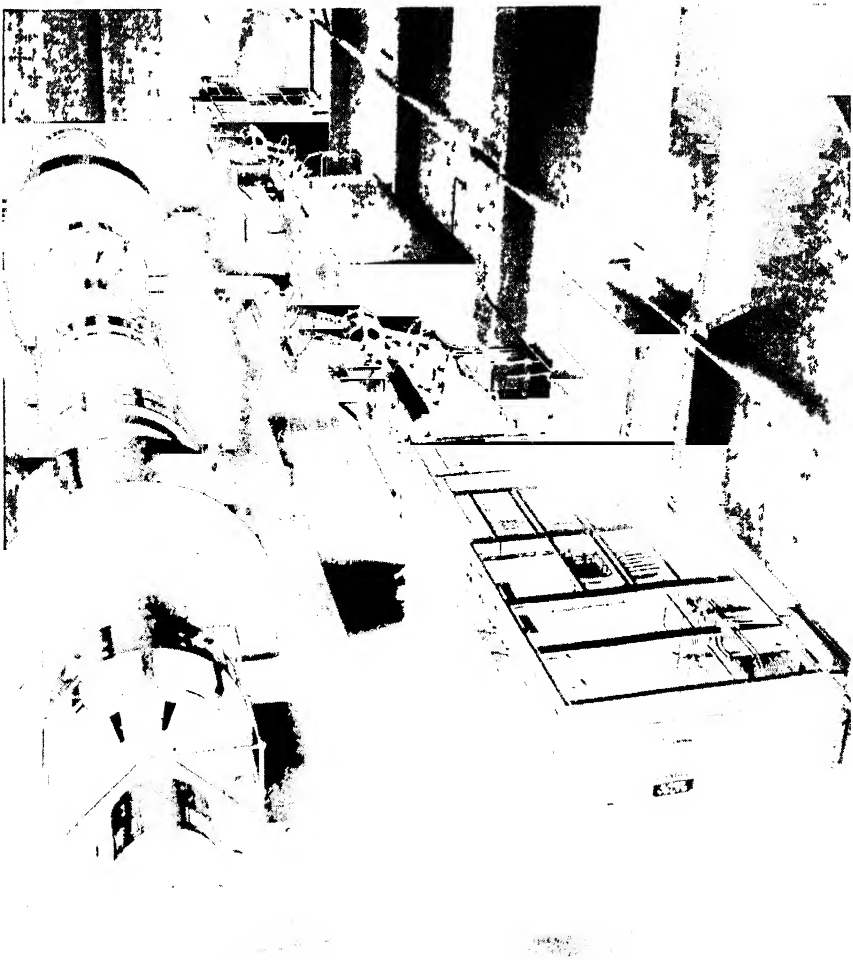


Fig. 162 —Equalizer flywheel hoisting set showing automatic liquid slip regulator

in the tank, known as the "electrolyte," is a solution of washing soda and water. By referring to Fig. 160, it will be seen that the movable electrodes are raised or lowered by a small torque motor *T*, which is energized from three series transformers in the primary circuit of the induction motor. The weight of the moving element is partly counterbalanced,

but it is still sufficient to move the plates together. The torque motor tends to separate the plates. This motor operates in the same manner as an ammeter; the plates move up or down until the torque of the motor just balances the weight of the moving element, which occurs at substantially the same current values for all positions of the plates. The friction in a commercial regulator does not require more than 5 per cent difference between the torque for raising and that for lowering the plates.

The upper curve in Fig. 163*a* shows the regulation obtained with one of these slip regulators in commercial work, as compared with the regulation obtained with a magnetic-contactor control for cutting resistance in and out of the secondary of the motor, as shown in the lower curve.

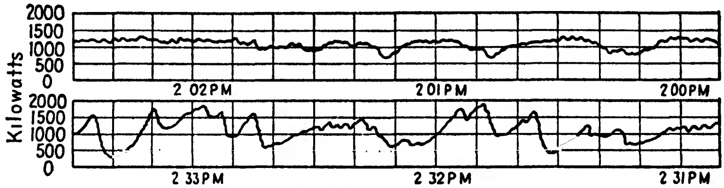


FIG. 163*a*.—Power-demand curves of a typical hoisting set. The upper curve shows regulation using a slip regulator; the lower curve, regulation using magnetic-contactor control

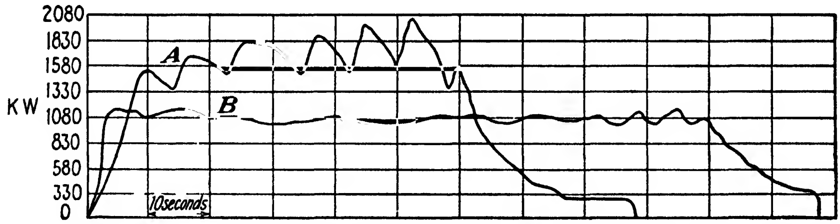


FIG 163*b*.—Curve *A* was taken when starting a 2,000-hp. plate-mill motor with magnetic control Curve *B* shows the same motor starting under load operated with a liquid regulator.

These curves, which reveal the advantages of the liquid regulator, show that the maximum-power input is quite uniform. The minimum-power input depends largely upon the way in which the load comes on and off the operating motor, so that these low peaks decrease to a very small value if the demand for power is small over a considerable period of time.

An exciter is shown mounted on the shaft of the motor-generator set in Fig. 160. As the speed of this exciter varies with the speed of the motor-generator set, it is necessary to provide a voltage regulator, in order that the voltage of this exciter will remain constant over the speed range that is obtained in practice. This is a simpler arrangement than the use of a separately driven exciter.

It is the practice of power companies to make a charge based upon the maximum demand required from the power system. This is a

just method of charging for power, as the size of the generating station must be determined by the maximum demand of the customers. Where a large motor is applied to a hoist, considerable power is taken from the line to accelerate the hoist if the motor is connected directly to the supply system. The charge for power may be large on account of this maximum demand. If the motor is operated from a flywheel motor-

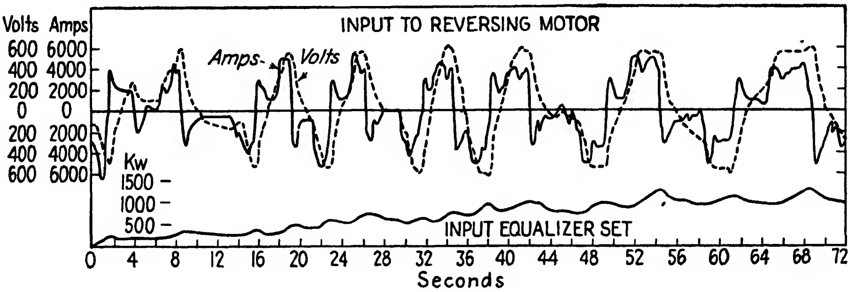


FIG. 164.—Input to reversing motor.

generator set, as was previously described, the maximum demand can be kept quite low, as is shown in Fig. 163, particularly if a liquid regulator is used, so that a reduction is made in the power bills by using this system. Another saving results from the regeneration of power when the load is reversed. In the operation of a mine hoist with this voltage system of controlling, there is very little rheostatic loss, so that less power is taken

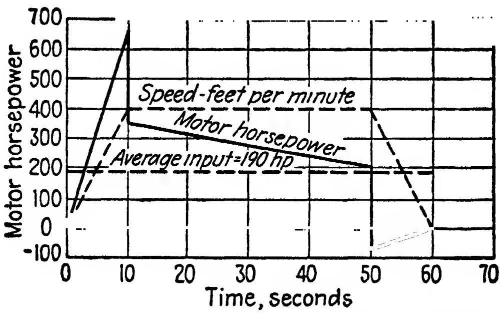


FIG. 165.—Load-time curve of a typical hoisting set.

and a large percentage of the energy given out by the descending hoist is returned to the line by regeneration.

It is not difficult to determine the size of a flywheel to absorb the peak loads when used in connection with a motor-generator set. A curve should be drawn showing the relation between the horsepower required at any particular instant and the time. It is usual to plot the horsepower as ordinates and the time as abscissas. From this curve the average input can be obtained and the maximum demand over any given period of time.

To illustrate, in Fig. 165 is given a load-time curve of a hoisting set, to lift 5,000 lb. at 1,200 ft. per min. The accelerating and retarding periods will be equal to 1,760 hp.-sec., and the constant speed periods will be 3,540 hp.-sec., making a total of 5,300 hp.-sec. in excess of the average requirements. This represents the total energy that must be given out by the flywheel over the maximum-demand period. This energy must be returned to the flywheel during the periods when the power demand is less than the average.

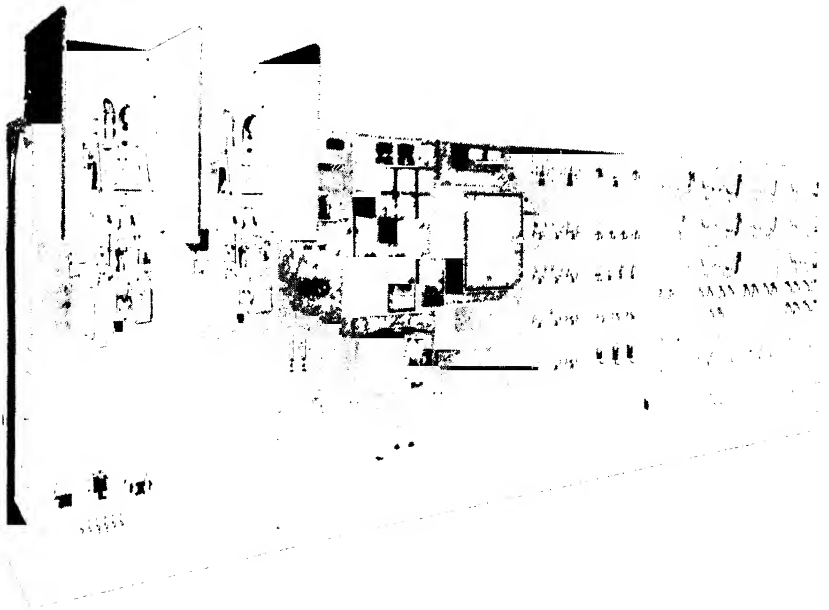


FIG 166 —Westinghouse control panel for a reversing steel-mill motor for main-roll drive

The weight of the flywheel depends upon the type of construction and the maximum peripheral speed. Let V_1 equal the velocity in feet per second at a radius of gyration for maximum speed, and V_2 for the minimum speed. The simplest form of flywheel and one of the best is made up of solid circular plates. For this type of wheel, the radius of gyration is equal to 0.707 of the wheel radius. If 20,000 ft. per min. is selected as the maximum peripheral speed, which corresponds to good practice, the maximum velocity at the radius of gyration will be

$$V_1 = \frac{20,000 \times 0.707}{60} = 236 \text{ ft. per sec.}$$

If a minimum speed is assumed equal to 85 per cent of the maximum speed, which is good practice, the minimum peripheral speed will be

$$V_2 = 236 \times 0.85 = 200 \text{ ft. per sec.}$$

The weight of the flywheel can now be calculated as follows:

$$W = \frac{\text{hp.-sec. to be supplied} \times 550 \times 2g}{V_1^2 - V_2^2} = \frac{5300 \times 35{,}400}{(236)^2 - (200)^2} = 12{,}050$$

The rotating element of the motor and the generator furnish some flywheel effect, so that the horsepower-seconds of the flywheel effect obtained from these two units can be subtracted from the total in calculating the size of the flywheel, if it is desirable to figure very closely.[1]

MULTIPLE OPERATION OF MOTORS AND GENERATORS IN SERIES

The scheme of control illustrated in Fig. 160 is applicable to mine hoists and similar reversing sets for driving the main rolls in steel mills. Many steel-mill applications require much larger equipments. If the diameters of the rotating parts are increased, the stored energy will increase as the square of the diameter, which materially increases the work required for reversing the requipment. It is, therefore, better engineering practice to divide motor and generator into two units. Figure 167 shows a diagram of the double-unit set. The main circuits between the generators and the motors might be arranged so that each generator operated its own motor, or the generators and motors might be coupled in series. The series arrangement is preferable, as it ensures an even distribution of load among all four machines. The objection to this arrangement is the large armature current if the voltage per machine is 250 or a total of 500 volts to ground; but if the voltage per machine is 500 volts, additional insulation is required. The arrangement shown in Fig. 167 avoids both these difficulties by connecting the motors and generators alternately in series, the current passing from generator No. 1 to motor No. 1, thence to generator No. 2 and motor No. 2, back to generator No. 1. This arrangement can be readily extended to additional machines if a larger output is required.

In rolling steel, it is very desirable that the motors shall have compound characteristics, but the armature currents are too large to reverse the series field each time the shunt field is reversed, so that another arrangement must be used. This consists of a small generator K (see Fig. 167), forming part of the exciter set. The fields of this generator are in series with the armature current of the main motors. The voltage of the machine K is, therefore, proportional to the load on the main motors, and this machine can be used to excite windings on the motors.

[1] With a slip regulator it is possible to keep the motor load almost constant at the average value. Without a slip regulator the motor load increases with the decreasing speed, and the calculation is more complicated. See S. A. Fletcher and Chas. R. Riker, Relation of Flywheel and Motor Capacity for Industrial Loads, *Elec. J.*, March, 1912, p. 270.

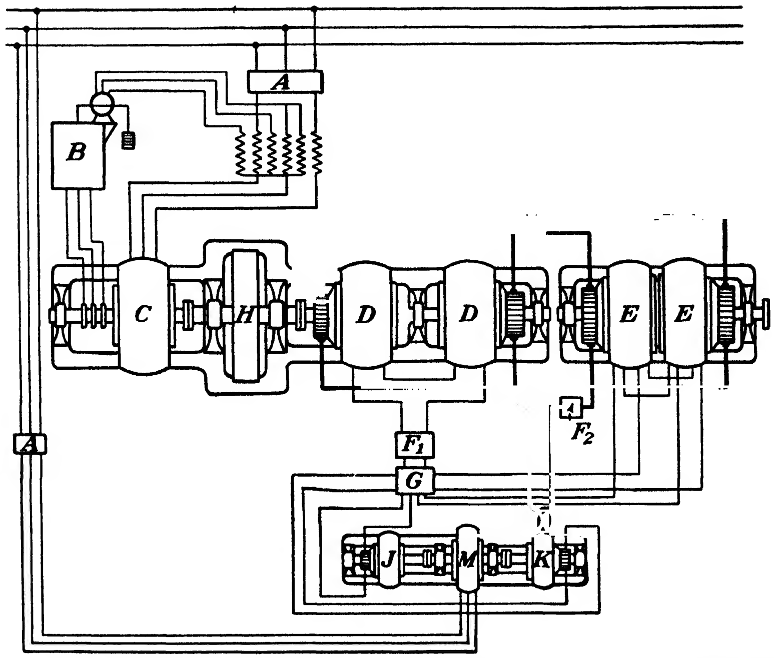
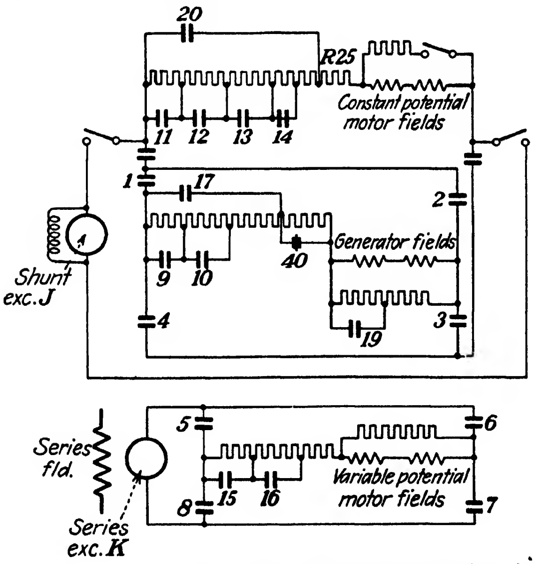


FIG. 167.—Connections for double-unit reversing motor. *A*, oil circuit breaker with no-voltage trip; *B*, automatic liquid slip regulator; *C*, a.c. wound-rotor induction motor; *D*, d.c. separately excited generators; *E*, d.c. separately excited motors; F_1, circuit breaker in generator fields; F_2, circuit breaker in main circuit; *G*, field controller; *H*, flywheel; *J*, shunt exciter for generator and motor fields; *K*, a.c. squirrel-cage induction motor.



Sequence of contactors

Sw	Forward						Off	Reverse					
1	O	O	O	O	O	O							
2								O	O	O	O	O	O
3	O	O	O	O	O	O							
4								O	O	O	O	O	O
5	O	O	O	O	O	O							
6								O	O	O	O	O	O
7	O	O	O	O	O	O							
8								O	O	O	O	O	O
9	O	O	O	O	O				O	O	O	O	O
10	O	O	O	O						O	O	O	O
11				O	O	O	O	O	O	O			
12			O	O	O	O	O	O	O	O	O		
13		O	O	O	O	O	O	O	O	O	O	O	
14		O	O	O	O	O	O	O	O	O	O	O	
15				O	O	O	O	O	O	O			
16		O	O	O	O	O	O	O	O	O	O	O	
17	Gen. field forcing voltage maintenance												
19	Gen field discharge												
20	Motor field strengthening												

FIG. 168.—Scheme of connections for reversing set.

These windings carry only a small current and can be reversed when the fields of the shunt generators are reversed.

The detailed scheme of connections for this reversing set is shown in Fig. 168. The control consists of a series of magnetic contactors, some of which are used for reversing the fields, others for changing the resistance in series with these fields, others for purposes that will be described later.

In order to make the generator voltage respond quickly to a change in the controller, it is necessary to wind this field for a low voltage and use a resistance in series with it. If this resistance is short-circuited while the field is being strengthened, it will increase the speed at which the change of flux takes place and therefore hasten the increase in voltage on the generator. This method of manipulating the field is called "field

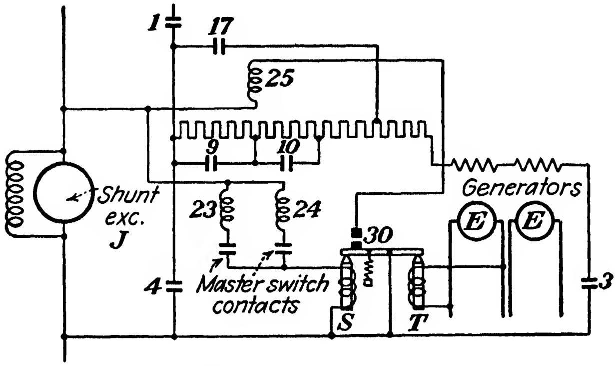


FIG. 169.—A method of preventing the field from building up beyond the value for which the master switch is set.

forcing." In order to prevent the field from building up beyond the value for which the master switch is set, an automatic arrangement is used, which is shown in Fig. 169. The coils for the contactors, 9 and 10, controlling the field, are shown as 23 and 24. These coils are in series with the solenoid S, which operates the contact mechanism, 30, and is opposed by solenoid T. The strength of S depends upon the coils 23 and 24 of contactors 9 and 10 being energized by the master switch. When a contactor is first closed, the coil S predominates over T and closes contact 30, which energizes coil 25 of contactor 17. This closes contactor 17 and short-circuits resistance in series with the generator fields. As these fields build up, the magnet T exerts an increasing pull until the desired voltage is reached, at which point magnet T overcomes S and opens contactor 17.

This contactor 17 is also used to maintain the generated voltage constant on long passes in the mill. As has been previously described, the motor-generator set is equipped with a flywheel, which by slowing down

furnishes the excess power above normal load. But the slowing down of the motor-generator set has a tendency to lower the voltage on the generators if the field strength remains constant. In order to overcome this difficulty and obtain constant voltage, which means constant speed of the mill motor, a voltage regulator is used, which momentarily closes contactor 17 whenever the voltage drops below normal. The voltage then tends to increase above normal so that by the repeated closing and opening of this contactor the field has a tendency first to increase and then to decrease, but, because of the inductive effect of the field circuit, the voltage remains practically constant.

An overload relay is used to limit the armature current. This relay is shunt wound, with as little inductance as possible, and is connected across the interpole windings of one of the motors, which acts as an inductive shunt, giving the relay a slight anticipation of a change in the current. But the change in flux in the generator fields has a time lag owing to the inductance of the field windings; therefore, when an overload occurs, if we arrest the increase of current in the field windings, the field flux will continue to increase on account of this stored energy. An overload relay that inserts resistance in series with the field circuit will not respond quickly enough to correct momentary current peaks. It is, therefore, necessary to add contactor 19, which short-circuits a section of the resistor in shunt to the field windings; this immediately arrests an increase in flux. The contactor 19 may open and close a number of times during a change in speed. It is found in practice that the various field windings can be timed so that dangerous overloads do not occur except during deceleration, when the motors are operating on weakened fields. This overload device is, therefore, arranged so that it operates only when the motors are delivering power to the generators.

The generator field has two sets of resistance in series with it. One set is controlled by contactors 9 and 10, operated by the master switch for the purpose of regulating the motor speed. The second set of resistance is normally short-circuited by contactor 40. When an overload occurs, it opens contactor 40, which inserts a resistance in the field, and this, in turn, reduces the current through the armature. Under normal operation, this contactor is closed.

The motors have two field windings, one connected to the constant potential source of power exciter *J* (see Fig. 167), the other connected to the compound exciter *K*. After the motors have reached normal speed on full field value, the speed may be further increased by weakening the motor fields. This requires the insertion of resistance in both field windings. If the fields are weakened too rapidly during acceleration, excessive current will flow through the armature. Contactor 20 is therefore provided for short-circuiting the resistance in series with the constant

potential motor fields. This contactor is controlled by an overload relay and opens and closes in rapid succession during acceleration, maintaining the armature current practically constant.

If the master switch is operated to decrease the speed of the motors, they will regenerate and in doing so reverse the polarity of the field windings supplied from the exciter *K*. This may cause an abnormal weakening of the motor field. To prevent this, a reverse-voltage relay opens contactor 5 or 6 and disconnects these field windings whenever the motor voltage reverses with reference to the generator voltage without the master switch's being reversed. As was explained previously, when the master switch is reversed, the polarity of these fields is automatically reversed; therefore, the current in these fields is in the correct direction.

The control of the reversing equipment for steel-mill service has been given at some length in order to illustrate the nature of the problems arising in such a control system. This control system is used for mine hoists and elevators with one working motor and no field control. Commercial controllers differ in many details, but the principles of this control are typical. Some of these problems are similar to problems met with in the control of small adjustable-speed motors. As an illustration, contactor 20, which prevents too rapid weakening of the motor field, has its counterpart in the ordinary fluttering relay used with adjustable-speed motors.

The control equipment for the rapid reversing required in steel-mill service differs in some details from the controller used with mine hoists, where the change in speed is much more gradual and the motor does not have compound characteristics. The mine-hoist controller provides automatic slow-down and stop at either limit of travel. This is accomplished by a current relay, which reduces the generator voltage to zero at the proper rate to keep the armature current at a constant value.

In order to prevent the generator fields from being disconnected from the line by throwing the master switch to the Off position when the motor is still running, a voltage relay is used, which automatically maintains the generator-field circuit and allows the decelerating current relay to slow the set down before disconnecting the fields.

When the generator field is disconnected from the line, there is a residual magnetism, which causes the motor to rotate at a very slow, creeping speed. This is a desirable feature in steel-mill work, as the slow turning of the main rolls prevents overheating and consequent injury to the rolls. When it is applied to a mine hoist, this creeping action is very objectionable. It is eliminated by automatically connecting the generator fields across the motor armature in the reverse direction. This causes a small current to flow through the field coils in the proper direction to kill this magnetism.

Steel mills, mine hoists, elevators, and planers are some of the principal applications using this method of control.

METHODS OF REGULATION

The motor-generator method of speed control of motors is developing wide possibilities. The generator can have a series field winding, to increase its voltage as the load increases, nearly to compensate for the voltage drop in the armature circuit and maintain approximately constant speed. This speed regulation is close enough for some applications, but where closer regulation is required, there are several designs of regulators available of the exciter type. Electronic tubes also can be used. It is desirable to keep the regulating power small and to amplify its effect on the generator voltage. These regulators can maintain exact preset speed or constant torque. They can regulate for any function that can be expressed electrically. The elements of the exciter type of regulators are as follows:

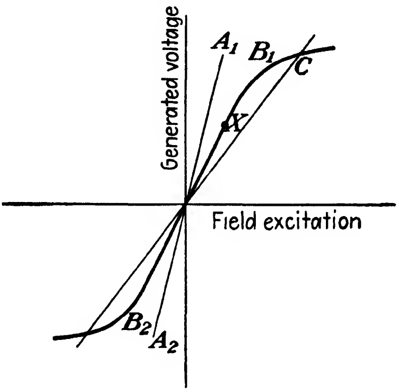


FIG. 170.—Saturation curve of an exciter.

The d.c. exciter, in Fig. 171, driven at constant speed, can have its self-excited field F_1 adjusted with a rheostat so that its magnetizing force coincides with the saturation curve in Fig. 170, line B_1-B_2. In standard practice the resistance is less and the line intersects the saturation curve at C. When the resistance is high, the magnetizing force moves toward line A_1-A_2, and the field flux becomes zero, as it will not self-excite. The field can be built up along B_1-B_2 to the point X by means of the momentary use of field F_2, which can move X up or down on B_1-B_2 by adding or opposing F_1. A small change in F_2 shifts the line of magnetizing force sidewise and a small field can make a large change in the exciter voltage. Field F_2 gives a regulating means requiring very little energy to affect the exciter voltage and is, therefore, very sensitive.

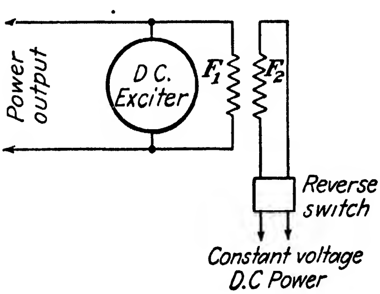


FIG. 171.—A regulating exciter with two fields F_1 and F_2, and means for reversing F_2. The rheostat in the circuit of F_1 is not shown.

The exciter in Fig. 172 has been given a third field F_3, which opposes F_1 and F_2. The rheostat R_2 selects the speed of the motor M_1. When this speed is reached, the voltage of RG causes F_3 to neutralize F_2 so that X in Fig. 170 remains on line B_1-B_2 at the point that gives the generator voltage necessary to run motor M_1 at its selected speed. When a change in load affects this speed, the voltage RG changes and the point X is moved to return RG to the set speed corresponding to the setting of R_2. In this way RG changes the position of X in Fig. 170 to excite G_1 to the proper voltage to cause F_3 to neutralize F_2 at the setting given R_2 and keeps the motor M_1 at its selected speed.

Changing the position of R_2 will select a new speed, at which the motor will be held constant. The Westinghouse Rototrol and the Allis-

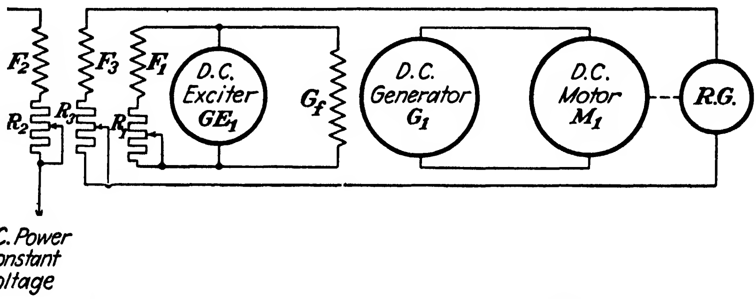


FIG. 172.—Method of regulating for constant speed. F_1, self-excited field; F_2, pattern field; F_3, regulating field; RG, generator with constant field drive by motor M_1.
The generator G_1 and the exciter GE_1 are driven at constant speed. R_1 adjusts F_1 so that the self-excited voltage is on the saturation curve (see Fig. 170) line B_1-B_2. R_2 adjusts the speed of M_1 and RG. F_3 opposes F_2 and the two are made equal by R_3 when the speed of M_1 is correct. An increase in the speed of M_1 reduces field GF and returns M_1 to the correct speed. A reduction in the speed of M_1 increases field GF and corrects the speed of M_1.

Chalmers Regulex both use this method of control, *i.e.*, a self-excited generator with the field magnetizing force coinciding with the straight part of the saturation curve and two additional field windings, the pattern field winding, which is adjustable, and an opposing or differential field winding, which is responsive to the function that is to be regulated. These last two fields, operating on the differential principle, require very little power. They neutralize each other when the regulation is correct. These machines are, therefore, amplifiers as well as exciters. If it is desirable, the self-excitation may be obtained by the use of a series field instead of a shunt field, as shown in Fig. 172.

The Westinghouse Company also uses the Rototrol in a Wheatstone-bridge connection, explained briefly in Fig. 173.[1] This bridge connection is very useful for certain applications.

[1] For a more detailed explanation, see G. A. Caldwell and W. H. Fornhals, Electrical Drives for Wide Speed Ranges, *A.I.E.E. Paper*, January, 1942.

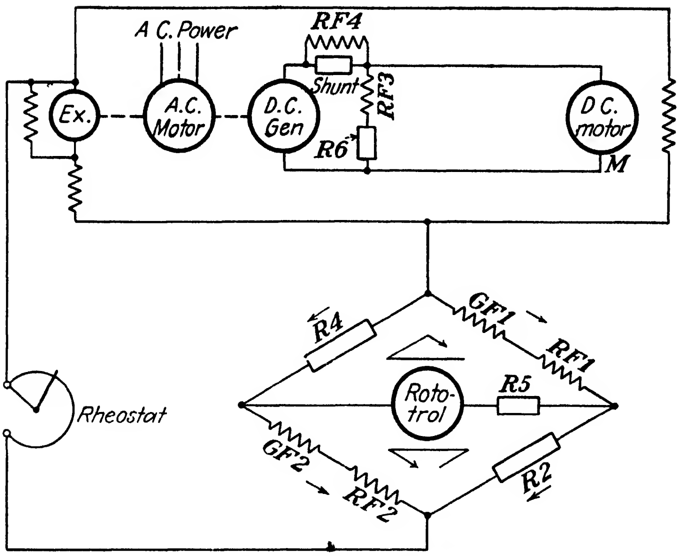


FIG. 173.—Rototrol with bridge connections. The generator has two shunt fields $GF1$ and $GF2$; the ampere turns add together. The Rototrol has four shunt fields—$RF1$, $RF2$, and $RF4$ ampere turns add together and $RF3$, ampere turns oppose the others.

At no load, $R5$ and $R6$ are adjusted so that $RF1 + RF2 - RF3 = 0$ and the Rototrol generates no voltage. The speed of the motor M is controlled by the rheostat. The no-load losses cause a current to flow in the shunt, which builds up $RF4$ and opposes $RF3$, causing the Rototrol to generate voltage and send current through $GF1$-$RF1$ and $GF2$-$RF2$, increasing the generator voltage to overcome the load-current voltage drop. $RF1$ and $RF2$ also increase to bring the Rototrol volts back to zero when M returns to its preset speed. The working load on M causes a further increase in the generator volts to compensate for the added voltage drop in the armature circuits.

If the load on M is negative, as when lowering a load, the ampere-turns in $RF4$ are reversed, causing a reduction in generator volts to hold M at its preset speed.

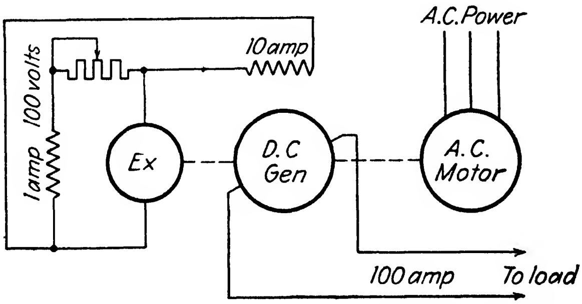


FIG. 174.—Shows how 1 ampere in the exciter field controls 10 amp. in the generator field and 100 amp. in the generator armature—an amplification of 100 to 1. This is one method of amplification where a slow response is satisfactory.

The General Electric Company uses a machine of the Rosenburg-generator or Pestarini-Metadyne type in which the armature cross field, set up by a pair of short-circuited brushes, supplies the power for the generator field. This machine, which is called an Amplidyne, is shown in Fig. 175 in simplified form. More complete information will be

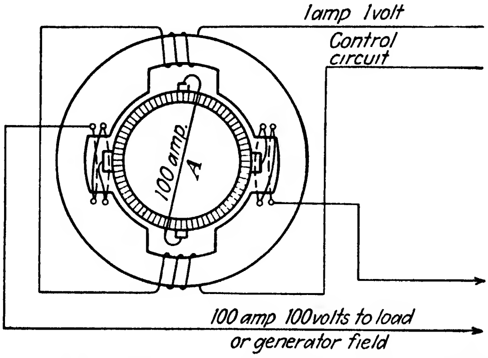


FIG. 175.—Amplidyne generator driven by an a.c. motor. Either generator—that in Fig. 174 or that above—can be used as an exciter for the field of a large d.c. generator of a variable-voltage motor-generator set controlling a working motor, such as a mine hoist. The control of the 1-amp. field circuit controls the voltage of the main generator. The response of the motor-generator set in Fig. 174 is slow as it works through two fields, and the ratio of field current and voltage to armature current and voltage is small compared with the Amplidyne generator. The power used in the Amplidyne-control field can be very small and controlled with electron tubes. The response is very fast, less than $\frac{1}{10}$ sec.

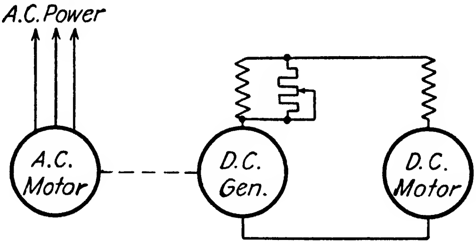


FIG. 176.—Variable-voltage control using a series-wound d.c. generator and motor. No exciter is required.

found in various technical papers.[1] The small amount of power used in the initiating field is greatly amplified by this machine.

Small variable-voltage motor-generator sets can be economically built with a series motor and generator. No exciter is required with this arrangement (see Fig. 176). The motor speed is adjusted by a rheostat in parallel with the generator field. The generator is usually driven by an a.c. induction motor.

[1] See ALEXANDERSON, E. F. W., M. A. EDWARDS and K. K. BOWMAN, The Amplidyne Generator—a Dynamoelectric Amplifier for Power Control, *Gen. Elec. Rev.*, March, 1940; also ALEC FISHER, Design Characteristics of Amplidyne Generators, *Gen. Elec. Rev.*, March, 1940.

CHAPTER XII

SERIES-PARALLEL CONTROL AND THE ELECTRO-PNEUMATIC CONTACTOR

SERIES-PARALLEL CONTROL

The series-parallel system of control is applied to two motors, or groups of motors, so arranged that they are connected in series across the line for acceleration to half speed and operation at this speed. The motors may then be connected in parallel and accelerated to full speed. The motors must be mechanically connected together. Otherwise, one motor may accelerate faster than the other. This results in unequal distribution of load. This control is usually applied to cars moving along a relatively horizontal track, such as street railway, interurban, and main-line cars and locomotives. It is also used for cars in steel mills, coke plants, etc., for the purpose of conveying material from one point to another. These latter cars may be controlled automatically by a push button or by a standard streetcar controller. This system of control is sometimes used for slope hoists, where the angle of the slope is small, and for the bridge travel of large ore bridges.

Some controllers are arranged for operation in either series or parallel, the motors being connected permanently in series or in parallel by means of a change-over switch. This switch is interlocked so that the controller must be turned to the Off position before the connections are changed. An arrangement of this kind is known as "series-and-parallel" control. It has a very limited application. If the resistor is designed for accelerating with one combination of motors, it gives poor acceleration on the other combination, unless the connections to the resistor are changed, which further complicates the control. The only occasion for using such a control would be where there are considerable periods of time during which the apparatus is required to operate at half speed, which can be obtained by series connection.

The series-parallel control is usually associated with street railway and steam railway electrifications; the system, however, is applicable to many industrial railways, to mining locomotives, automobile trucks, and similar applications.

Advantages.—The advantages of the series-parallel control are obtained when the period of acceleration extends over a considerable period of time and represents an appreciable part of the complete duty cycle. This is obtained in horizontal traction and in many of the

applications already enumerated. A saving is accomplished when the motors are connected in series, since the current drawn from the line is one-half the value that would be taken if the motors were connected in parallel. This is particularly desirable for starting a car or a train of cars where the static friction requires a considerable torque in excess of the running torque. Where the period of acceleration is short, the saving is often counterbalanced by the loss during the transition period.

The series-parallel control gives operation at one-half normal speed. This is desirable where trolley cars are operated through a congested portion of the city. If the industrial car is operated automatically, the series combination would give a low speed, from which the stop could be made more gradually than from the parallel combination. The reduction in starting current may sometimes permit the use of smaller feeders for a trolley system or other power distribution. The acceleration of the motors in series to half speed, and then in parallel to full speed, results in a saving in the weight of the resistors, which is considerably more than the additional weight to the control equipment, so that a net saving in the total equipment is obtained.

Limitations.—The disadvantage of the series-parallel control is the added complication in additional parts to the controller. Where rapid acceleration is required, the transition period from series to parallel introduces a time element, which is objectionable. For instance, many industrial motors are accelerated in approximately 3 sec. If 1 sec. were taken for the transition period, this would add 33 per cent to the total time of acceleration. If the complete cycle were completed in 6 sec. or 10 times a minute, the introduction of this extra second would eliminate one cycle per minute, which might be very undesirable. Even where the bridging system is used and no loss is experienced in the progressive acceleration, the additional time required for the operation of the extra switches would still add a considerable time element to the cycle. Where the motor operates a vertical hoist or has a similar load, the reduction in torque, which usually occurs at the transition period, would cause a slowing down of the motors. This would be very undesirable and would more than compensate for any saving that might be effected during the period of acceleration of the motors in series.

Where the series-parallel system is considered for a new application, careful analysis should be made of the accelerating conditions, to determine whether this system of control is the most desirable.

Methods of Transition.—There are three common methods of changing motors from series to parallel. They are known as

1. Open-circuit transition.
2. Shunt transition.
3. Bridging transition.

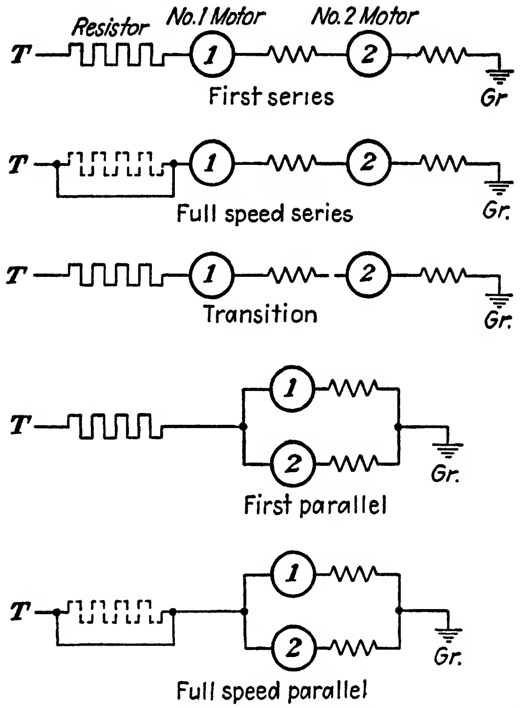


FIG. 177.—Steps in the open-circuit transition method of series-parallel control.

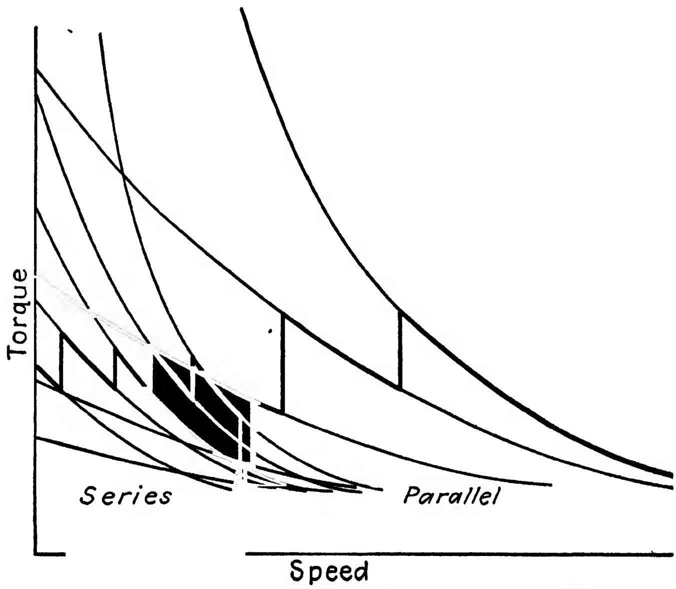


FIG. 178.—Speed-torque curves with open-circuit transition.

Open-circuit Transition.—This was the first method to be introduced. It is illustrated in Fig. 177, while Fig. 178 shows the relation between speed and torque during acceleration. In passing from the full series to the first parallel notch, the circuits of both motors are opened.

This method is in use for small motors in ordinary service. It is objectionable because the motor circuits are opened, causing arcing at the contacts of the controller and a loss of torque in the motors. The method of control is simple and easily understood. The motors are per-

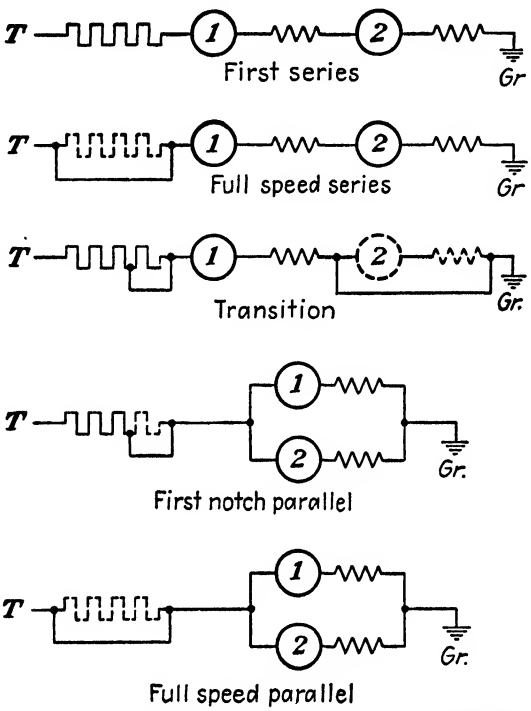


FIG. 179.—Steps in the shunt-transition method of series-parallel control.

manently connected in series and started by inserting resistance in series with them. This resistance is gradually short-circuited, as in rheostatic control. This gives half speed with both motors the line in series. The motor circuits are then opened and the motors are connected in parallel and accelerated from half speed to full speed by introducing resistance in series with each motor, and gradually short-circuiting it.

Shunt Transition.—The method of shunt transition is an improvement over that of open-circuit transition. It is based on the principle that a short circuit can be placed around the armature and fields of a series motor without injuring the motor. The short circuiting of the armature through the field reverses the field current, which, in turn,

reduces the fields and counter e.m.f. to zero. The method of control is shown in Figs. 179 and 180. This system allows one motor to remain active while the other is being short-circuited, and in this way an active torque is maintained on the apparatus during the transition period. In passing from full-speed series to the first notch in parallel, the proper amount of series resistance is first inserted and then motor No. 2 is short-circuited. This resistance limits the current to compensate for the absence of the counter e.m.f. of motor No. 2. This motor is then connected in parallel with motor No. 1, and the series resistance gradually

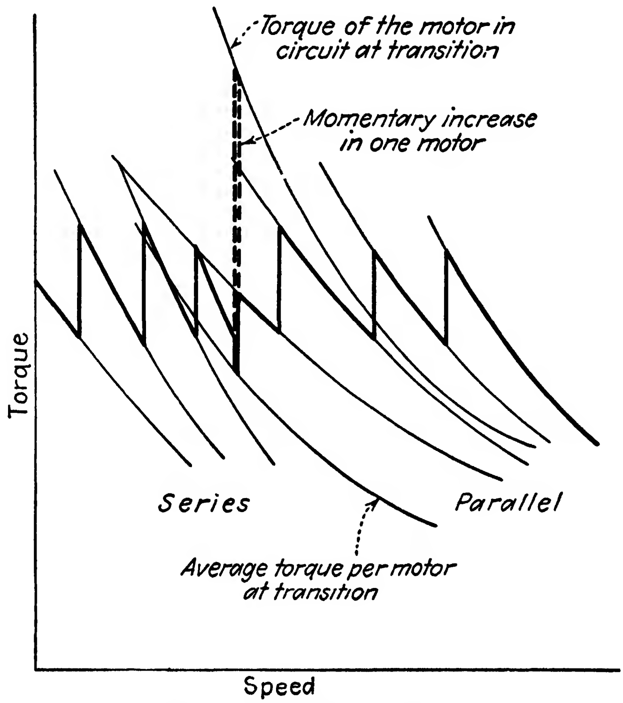


FIG. 180 – Speed-torque curves with shunt transition.

is short-circuited until the motors are connected across the line, giving full speed. This method of control is employed in the type *K* drum controllers, which are still in extensive use on trolley cars.

One of the type *HL* electropneumatic controllers uses this principle of control. Figure 181 shows the connections in detail. An improvement has been made in this controller by using some of the sections of resistors several times. This is permissible, as the use of resistors in series requires the short-circuiting of these resistors in sections. Ordinarily, the first section of the resistor has the maximum resistance and is in circuit the shortest length of time. In order that cast-iron grids may be used

for these resistors, this first section usually has more capacity, and requires less capacity in proportion, than the balance of resistors, as it is impractical to obtain high ohmic value with a small number of grids. If this section of resistor is now used in another part of the acceleration by

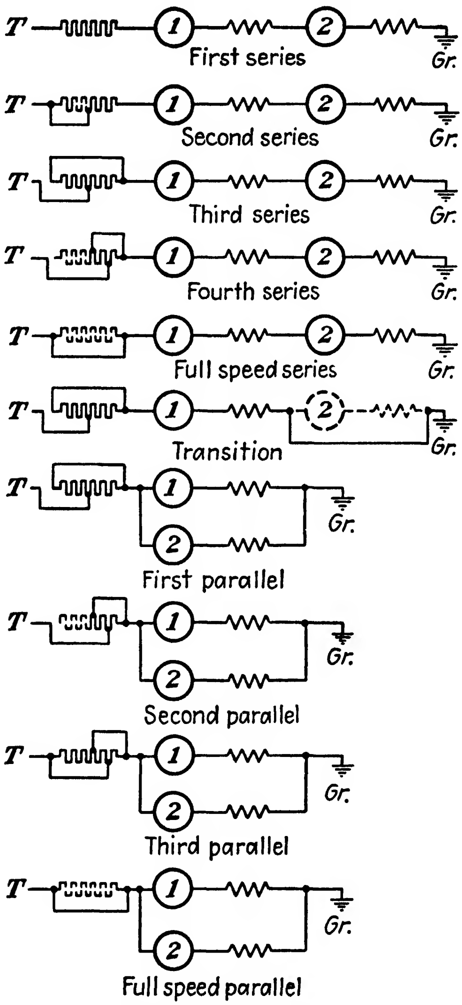


FIG. 181.—Steps in shunt transition using an electropneumatic controller.

being connected in parallel with other resistors, the weight of metal is used to better advantage and the total weight of the resistor is reduced.

The advantages of this method of transition are that

1. An active torque is maintained upon one motor during the transition period.
2. It is the simplest method in general use.

The disadvantages of this method of transition are that

1. A reduction in torque is obtained during transition, as only one motor is active.
2. This active motor is subject momentarily to a very heavy overload.
3. The change in torque on the short-circuited motor during transition usually results in the motor's being momentarily driven by the other motor, which takes up the lost motion in the driving gears in the reverse direction. When the motor becomes active again, this lost motion is again taken up in the positive direction. This double action results in two shocks in the driving machinery and has a tendency to cause excessive wear and loosening of parts.

Bridging Transition.—The transition from series to parallel by this system consists in placing a shunt, or bridge, between the motors so that

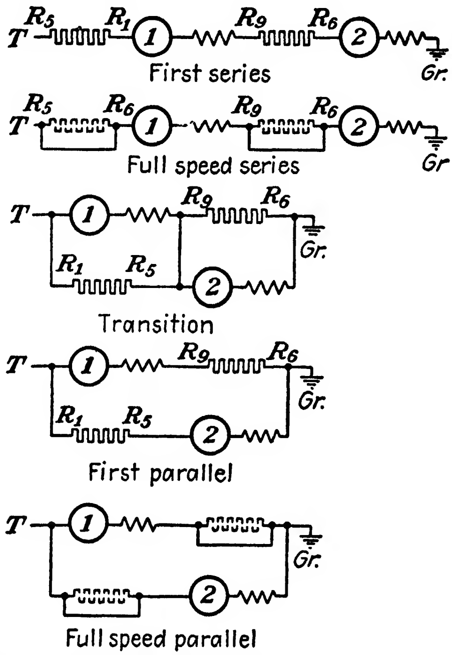


FIG. 182.—Steps in the bridging-transition method of series-parallel control.

all the motors are active during the transition period. This is illustrated in Figs. 182 and 183. Its operation is similar to that of a Wheatstone bridge. The two sides of the bridge consist of the motor plus a resistor. If the drop in voltage through the resistor is equal to the drop through the motor, the two parts of the circuit connected by the bridge will be at the same potential, and no current will flow. It is difficult to obtain this exact balance with manual operation; it can be closely approximated, however, where automatic acceleration is used. The arrangement of circuits for this method consists in a portion of the series resistance being inserted between the two motors. Passing from the full-speed series posi-

tion to the first parallel notch, the two sections of resistance are inserted in parallel with the motors, so that each motor has a circuit from trolley to ground through the motor and a section of resistance, the final series connection forming the bridge of the circuit. This bridge circuit is then opened and the resistance is gradually short-circuited until the motor is brought up to full speed. In practice, extra resistance is inserted ahead of the first motor, to obtain adequate starting resistance and to protect the first motor on resetting the circuit breaker.

If the resistors are so adjusted that more current passes through the two resistors than through the two motors during the bridging period, the opening of the bridging switch will interrupt this excess current and give

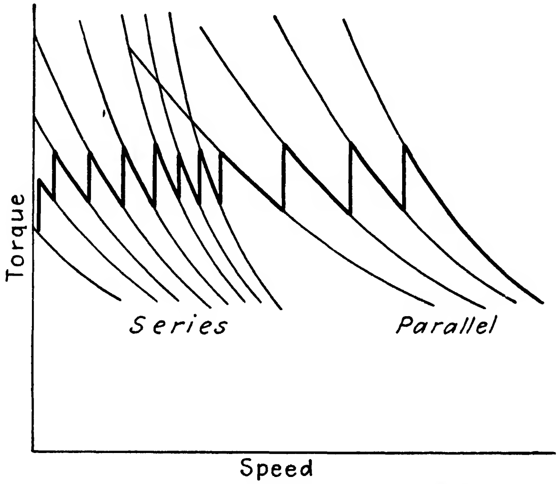


FIG. 183.—Speed-torque curves with bridging transition.

an increased torque on the motors, equivalent to an additional notch of the controller. This notch can be so adjusted as to be equal to the other accelerating notches, so that the acceleration through the transition period compares favorably with that during other periods.

The advantages of this method of control are that

1. An active torque is maintained on the two motors during the transition period.
2. By proper adjustment of the resistors at the time of transition, an active accelerating notch is obtained at this time, which gives a smooth acceleration. Since both motors are active, no jerks are produced. These advantages make this method of transition the best for heavy-traction applications.

The disadvantages of this method of control are

1. Added complication.
2. Additional switches.
3. Increased arcing. This latter is objectionable only where drum controllers are used. Contactor switches are well adapted for this service and the arc can be properly distributed so as not to cause excessive wear.

ELECTROPNEUMATIC CONTROL

The use of series-parallel control in railway work has identified it with the electropneumatic controller. This controller is in general use for

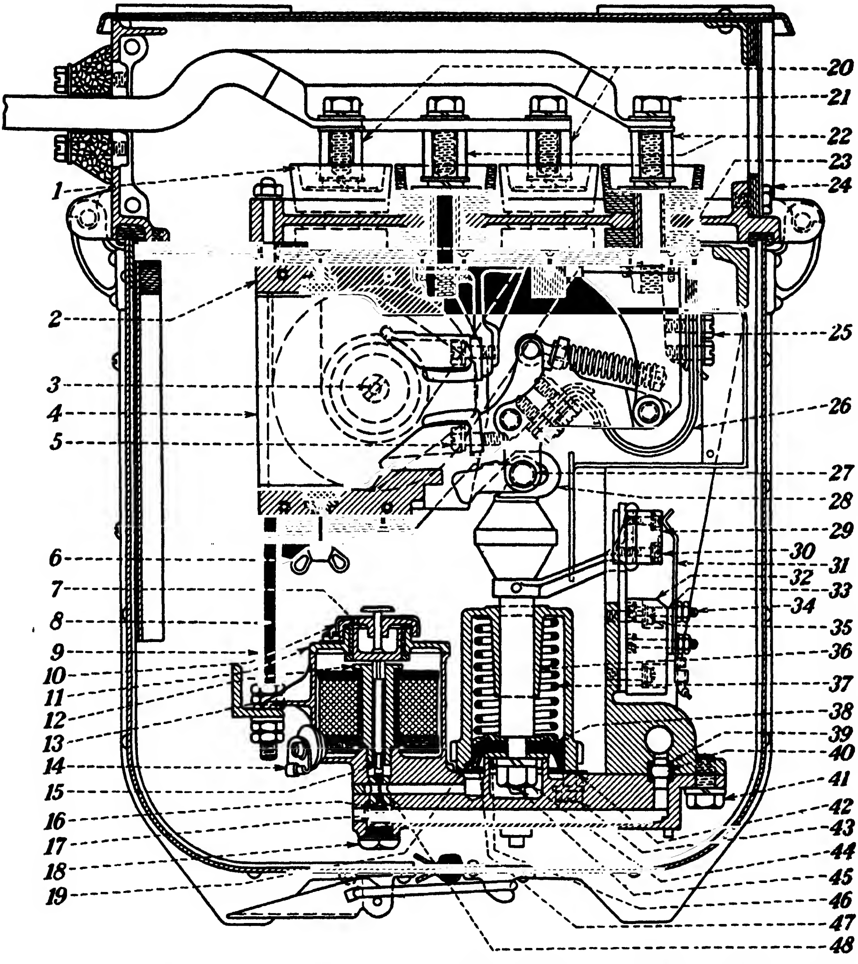


FIG. 184.—Cross section of an electropneumatic switch: 1, insulating washers; 2, arc chute; 3, screw holding pole piece on blowout coil; 4, arc-chute side; 5, bolts holding switch contacts; 6, wing nut holding arc chute in place; 7, armature of magnet valve; 8, bolt holding angle iron that supports front end of valve-magnet casting; 9, insulating tube; 10, magnet-valve cap; 11, iron cover of valve magnet; 12, magnet-valve core; 13, foot supporting front end of magnet bracket; 14, magnet-coil terminal.

railway work but is also used for some industrial applications where compressed air is available, or where the installation is of sufficient size to warrant the use of compressed air. Often compressed air proves a valuable means for operating mechanical brakes, clutches, and similar

apparatus, so that on some large ore bridges and similar industrial applications, the electropneumatic controller has been used instead of the magnetic-contactor controller.

Electropneumatic Switches:—When the railway industry developed from small individual cars to multiunit operation, it became necessary to design control apparatus that could be operated from a master switch placed on the platform of the leading car. Several methods of operating the control were tried. The two principal methods used at that time, both of which are now in successful operation, were the magnet-operated contactors and the electropneumatic switch. Other methods, such as the pilot motor-operated and air-cylinder-operated controllers, have been used, and still have a limited application, but the railway industry today has been built up on the foundation of individual contactors or switches operated either by a magnet directly or by air pressure controlled by an electromagnet.

The switch is illustrated in Fig. 184, which gives a cross-section drawing of the switch. The contacts are of the rolling type, having the same design as those of the magnetic contactor. They are opened by a spring in the air cylinder and closed by air pressure underneath the piston. Air is admitted to the cylinder by a small valve operated by a magnet. The work done by this magnet is so small that a very low wattage in the coil is sufficient for the purpose. This makes it possible to design a small magnet that will operate over a wide range of voltage and one that can be used on a low potential circuit. The design of the switch is such that a failure of air pressure results in opening the switch. The magnetic blowout is smaller in design than those used for magnetic contactors, with possibly one exception. The opening in the arc box confines the arc to a movement in the horizontal direction. This is necessary in order to permit the mounting of the switch underneath a car or in rows in a locomotive cab. As was explained in a previous chapter, the arc is ruptured by stretching it and cooling it. On account of the arc's being moved only in the horizontal direction, the arc box on the railway contactor is usually larger than that for the corresponding industrial contactor, which permits the arc to be moved both horizontally and vertically. In other words, the industrial contactor has a box that is opened at the top as well as the side.

The width of the switches for railway service is kept down to a minimum, in order to reduce the over-all length of the controller, which is made up by mounting switches side by side. Weight also is an important factor influencing the construction of the switch. This is evident from the minimum amount of iron used in the framework. The latest designs of these switches are of the self-contained unit type, the switch parts being clamped to insulated steel bars, which form the framework of the

switch and give the maximum strength with a minimum weight. This unit construction permits the air-operated switch to be assembled in a variety of ways, the more readily to adapt it to different classes of service. The former method of building these switches in groups of eight to ten in a cast-iron frame resulted in a heavier controller—one that lacked flexibility.

The arrangement of air-operated switches shown in Fig. 185 is typical for an ordinary surface car. The switches are mounted in a sheet-metal enclosure, which protects them from dirt and water. The sides of the box are hinged, to make the operating parts of the switch accessible for inspection and renewals.

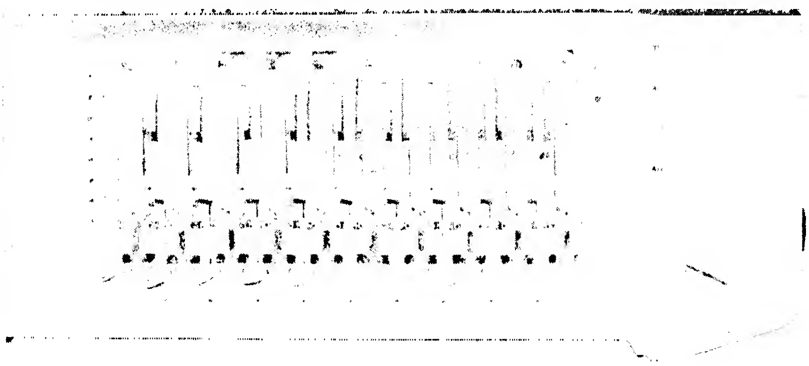


FIG. 185.—Arrangement of air-operated switches in the ordinary surface car.

The controller is divided into two groups, one of which carries the reverse switch and the other the sequence switch. The sequence switch is a small drum controller actuated by air cylinders and controlled by magnet valves. The contact fingers energize the air switches in the proper sequence for accelerating the motors. The speed at which the sequence-switch drum rotates is adjusted to give the desired rate of acceleration. When the master switch is moved to the Off position, the sequence switch returns to its initial starting position. This ensures that the motors are started in the proper manner each time the master switch is moved from the Off position to one of the running notches. The sequence switch will stop at intermediate notches corresponding to positions on the master switch. The reverse switch is interlocked with the line switches, so that it is operated only when the controller is disconnected from the line.

The valve magnets are operated on a low-potential circuit, which is supplied either by a storage battery or from a resistance that is connected

across the line, the valve magnets being in shunt with the portion of this resistance at the grounded end. The voltage used on the valve magnets is normally 20 volts. On account of the low voltage at which the valve magnets operate, there is very little arcing on the interlock fingers, which permits their being arranged in a very compact manner.

The use of air as an auxiliary for operating the controller has been applied to a number of different types of control. Air pressure is available at the present time on practically all except very small surface cars. The amount of air used in operating a controller is small in comparison with the amount taken by the air brake, so there is little objection to using air as an auxiliary for operating the controller. The only extra precaution required is to see that the piping is installed so as to drain the moisture from the air system. Air cools very rapidly when it is expanded and has a tendency to cause frost or ice particles to form in the ports to the valve and the cylinder, particularly when the outside temperature is very low. This difficulty is sometimes experienced when the piping is installed by persons not familiar with this system of control. If it is properly installed, the air is cooled after being compressed, which precipitates the moisture in the form of water that can be readily drained off. The only other source of trouble is dirt, which can be easily removed by a fine-mesh strainer.

An important detail of these switches is the piston leather. There is perhaps no detail of the entire switch that has received more thought and on which more research work has been done than on the piston leather and the method of mounting this leather in the cylinder. Leather is porous and, if it is used in its natural condition, it will have excessive air leakage through these pores. It is therefore necessary to treat this leather, partly for the purpose of filling up the pores and partly for the purpose of giving it the proper mechanical structure. The practice at this time is to use a piston leather made up of three layers, or thicknesses, of leather. This gives the desired flexibility as well as reducing the leakage to a minimum. The piston leather has a phosphor-bronze expander, mounted inside the cup. This causes the leather to exert an initial pressure against the inside of the cylinder. When air is applied, this pressure is increased and makes a tight joint between the leather and the walls of the cylinder. The compound with which the leather is impregnated must withstand a considerable variation in temperature. In cold weather the cars may be idle for a long time and the temperature within the cylinder may go to zero or even lower. When the car is in service, the current that passes through the controller heats up all the parts in the switch group and, if the outside temperature is warm, especially in the southern states, the temperature inside the cylinder becomes very high in comparison. The ordinary compound with which leathers are impregnated

has a tendency to be very stiff at low temperatures and very soft at high temperatures. It is therefore necessary to use a process for impregnating that will give satisfactory operation over wide range of temperature.

Advantages.—The electropneumatic control has a number of fundamental advantages, which may be briefly summarized as follows:

1. High pressures can be used between the contacts carrying the main current.
2. A strong spring can be used in opening the contacts.
3. The valves require very little force to operate them and the magnets require only a small wattage for their successful operation.
4. On account of the above, successful operation can be obtained with a wide range of voltage on the control circuits.
5. The power available for operating the switch permits a rugged construction of the interlock contacts.
6. The low voltage at which the valve magnets operate permits of a very compact arrangement of interlock details.
7. The design of the switch is such that its operation is independent of its position and is also independent of vibration.
8. The speeds at which the switch opens and closes can be independently adjusted by changing the size of the air inlet and exhaust.
9. The switch closes at a positive uniform speed and eliminates the hammer blow present in magnet-operated contactors. This reduces the bouncing of the contacts during closing to a minimum and in many cases entirely eliminates it.
10. The pressure on the contacts carrying the main current is independent of the line voltage. With control of this type, being independent of voltage, the car can be operated at any voltage that will cause the motors to turn over. On the other hand, the movements of the switch will be uniform and satisfactory at voltages greatly in excess of normal.
11. On account of the small size of the valve magnet, it has very little induction and therefore responds quickly both in opening and in closing the valve; the small inductive effect does not interfere with the coils connected in multiple.

Limitations.—The limitations of this form of control may be summarized as follows:

1. It requires a reliable source of air pressure for operation. The normal air pressure is usually 70 lb. This air pressure should not drop below 50 lb. and should not exceed 100 lb. In practice, a governor maintains the air at normal pressure, so that the switches may operate under the most favorable conditions.
2. The air must be clean and dry.
3. The use of air as an auxiliary requires piping connections to be made to the controller, in addition to the wiring connections. This is offset to a considerable extent by the use of low-voltage control circuits, which simplifies the wiring details.
4. Piston leathers need renewing from time to time. This, too, is offset somewhat by the absence of trouble with the valve magnets and interlocks on account of the small power used in this circuit.

CHAPTER XIII

ADJUSTABLE-SPEED ALTERNATING-CURRENT MOTORS OF THE WOUND-ROTOR TYPE

ANALOGY WITH D.C. ADJUSTABLE-SPEED SETS

The wound-rotor induction motor can have its speed adjusted by connecting the secondary circuit to an external source of power having suitable characteristics. The principle of operation may be illustrated by referring to a similar scheme using d.c. machines. If we assume a d.c. motor A (see Fig. 186), having a d.c. machine B in series with its armature, and assume that this d.c. machine is operated at a constant speed by another d.c. machine C, it can be readily seen that by changing the voltage of this regulating machine B, the speed of the main motor A can

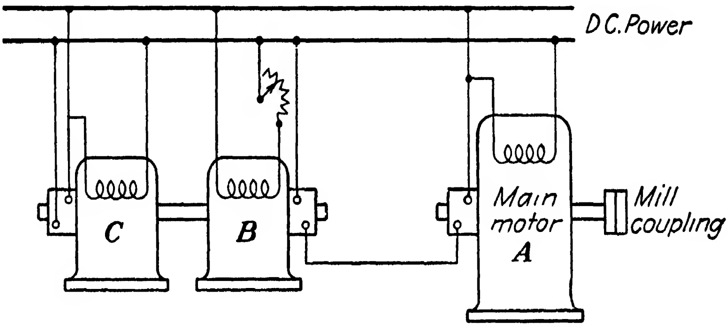


FIG. 186. Direct current adjustable-speed set, constant torque.

be adjusted. Assuming that B runs at constant speed and that its field is capable of adjustment over a wide range and that it is provided with interpoles, so that it will operate successfully at zero field strength, we can then obtain a voltage from B that either opposes the flow of current through the motor A or assists that current. In other words, the machine B interposes an active voltage in the armature circuit of machine A. This voltage may oppose the line voltage, reducing the speed of A below normal or it may add to the line voltage, increasing the speed of A above normal voltage. If we wish to reduce the speed of motor A 50 per cent, the machine B would have half the capacity of A. When the motor A is operating below normal speed, the difference in power represented by this difference in speed is absorbed by the machine B, which acts as a motor driving the machine C as a generator and returning this power to the line.

If the motor A is operated above normal speed, power is taken from machine B, which then becomes the generator, and machine C a motor receiving current from the line. The torque of machine A remains constant throughout the speed range, as this torque is fixed by the field strength, which is assumed to be constant, and the current-carrying capacity of the armature. Therefore, this equipment operates at a constant torque throughout its range, the horsepower varying with the speed. (These statements and those that follow are all based on the assumption that the equipment is operating at its rated full-load current.)

If we couple the machine B to the main motor A, as shown in Fig. 187, the speed of A can be adjusted in a manner similar to that shown in Fig. 186, by varying the field strength of machine B. In this case, the difference between the operating speed and the normal speed of the main motor A is absorbed by the machine B and converted into mechanical

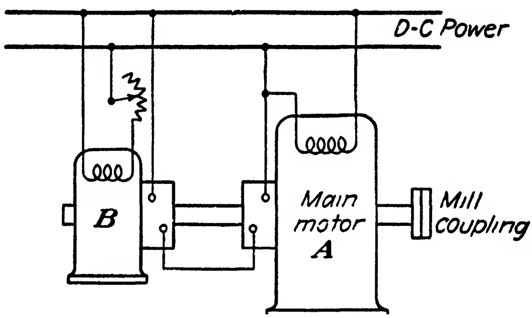


FIG. 187.—Direct current adjustable-speed set, constant hp.

work. The torque of A remains constant, but the torque of B will change with the change of speed, the resultant torque of the equipment being inversely proportional to the speed and the horsepower remaining constant.

In the schemes shown in Figs. 186 and 187, it will be noted that the main current passes through machines A and B in series. Assuming that this current is always equal to full-load current and that the supply voltage is constant, it will be seen that the power supplied to this circuit has a constant value. In Fig. 187 there are no other connections to the line and, therefore, if the losses are kept small this scheme should deliver a constant horsepower corresponding to the constant-power input. The arrangement in Fig. 186, however, provides an additional circuit through machine C. There is a constant-power input to machines A and B, to which the power input of machine C should be either added or from which it should be subtracted, depending on whether machine A is running above or below normal speed. The total power received from the line is, therefore, a function of the speed. The torque, however, is obtained

from one machine only, namely the main motor A. Therefore, this equipment delivers a constant torque, as compared with the constant horsepower delivered by the equipment in Fig. 187.

If these two schemes are kept in mind in considering the a.c. motor, it will be found that the methods used for controlling this motor are either constant torque or constant horsepower and that they function in a manner similar to that of the d.c. motor.

The line voltage connected to the primary of an induction motor must be balanced by a counter voltage set up in the windings caused by the alteration of the flux through these windings. This counter voltage is a little less than the line voltage, the difference being consumed by the ohmic and leakage reactance drops caused by the load current. Assuming that the line voltage, the frequency, and the load on the motor remain constant, the primary flux remains constant. Most of this flux also passes through the secondary. If the secondary revolves at synchronous

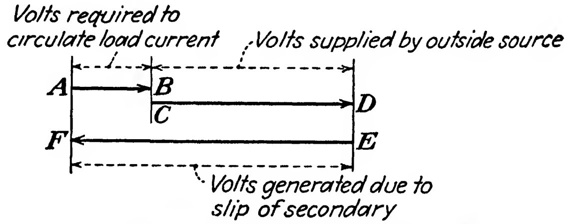


FIG. 188.—Secondary-voltage distribution; motor operating below synchronism.

speed, its conductors do not cut this flux and there is no secondary voltage or current; therefore, no work is done by the motor. In practice, the secondary revolves at a little less than synchronous speed. This difference in speed generates a secondary voltage, which causes the secondary load current to circulate. This, in turn, requires a corresponding increase in the primary current in the ratio of transformation. The difference between synchronous speed and actual speed is commonly called the "slip" of the motor. Let us assume that this slip amounts to 3 per cent of the synchronous speed of the motor. The motor, therefore, operates at 97 per cent of synchronous speed at full load. If we now connect the secondary circuit to a source of power of the same frequency, we can impress an external voltage upon the secondary windings. If this impressed voltage has the proper phase relation, the secondary will revolve at a less speed, as more slip will be required to generate the additional voltage made necessary by that supplied from the external source. This can be more easily understood by referring to Fig. 188. We will let the line AB represent the amount and direction of voltage required in the secondary to circulate the load currents and the line CD the voltage supplied from the external source. We must then generate in the second-

ary circuit a voltage EF, which is opposite to the two previous voltages and equal to their sum. In order to generate this voltage, the secondary must run at a less speed. The motor can be operated above synchronism by changing the direction of the voltage supplied from the external source. Figure 189 shows a similar analysis. The line AB represents the value and direction of voltage required to circulate the load current. This is the same as in Fig. 188. The line CD now represents the value and direction of the voltage supplied from the external source. The secondary of the motor must, therefore, develop a voltage having a value and direction corresponding to EF. As this voltage is in the opposite direction to that in Fig. 188, it is necessary for the motor to operate above synchronism.

Figures 188 and 189 show that, when the motor is operating below synchronism, the voltage required to circulate the load current is obtained by a decrease in speed and, therefore, by less work being delivered by the

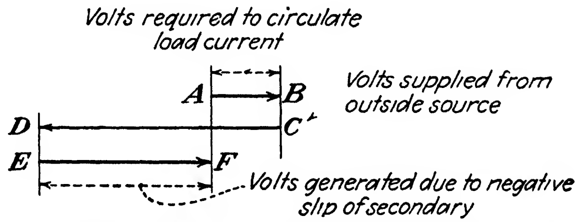


FIG. 189.—Secondary-voltage distribution; motor operated above synchronism.

motor. When it is operated above synchronism, this voltage is supplied as part of the power obtained from the external source. In both cases the voltage required to circulate the load current represents a loss; in one case the loss appears as less mechanical work, while in the other case the loss is made up from a source of power external to the motor itself.

ALTERNATING-CURRENT ADJUSTABLE-SPEED SETS

The performance of the a.c. machine is similar to that of the d.c. machines previously described, with the additional limitation that in the a.c. machine we must take into consideration the power factor and frequency of the circuits in the secondary of the motor, in addition to the voltage. In the d.c. machine we are concerned only with voltages. In both a.c. and d.c. machines the speed of the motor can be adjusted either above or below normal speed by changing the voltage impressed upon part of the motor windings from an external source.

Several different methods have been used for introducing the variable voltage in the secondary circuit of a wound-rotor motor. Some of these methods also include means for changing the power factor so that the normal power factor of the motor may be improved or even changed to

a leading power factor. In all these methods the main motor is started from rest by connecting the secondary through a resistor with means for short-circuiting this resistor, as is done with standard equipments. The diagrams in Figs. 190 and 191 show this resistance, together with a change-over switch for connecting the motor to the adjustable control after it has come up to speed. This method of starting has been omitted from all except Figs. 190 and 191 for the purpose of simplicity, as the means of starting has nothing to do with the principle of speed adjustment.

In describing the following methods no attempt will be made to develop the theory or to furnish vector diagrams illustrating the phase relation between the different voltages and currents. A very complete analysis of these problems is given in the A.I.E.E. proceedings.[1]

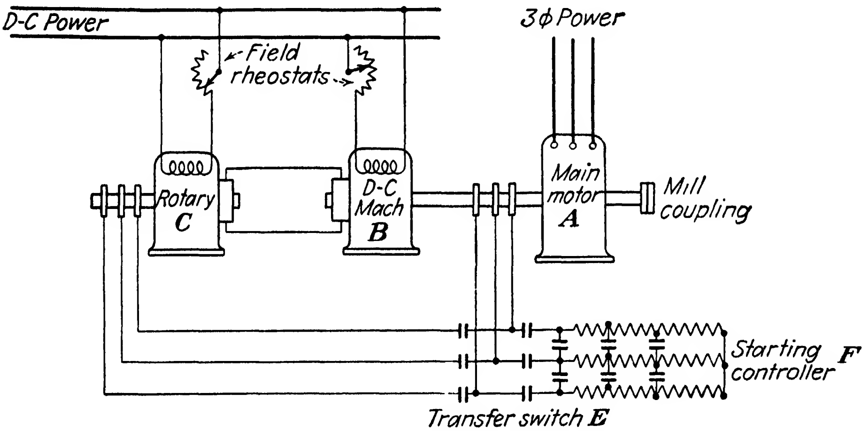


FIG. 190. Method I, constant hp.

Method I.—This method consists of a main driving motor coupled to a d.c. machine. The secondary of the main motor is connected to the slip rings of a rotary converter. The d.c. side of the rotary converter is connected to the armature of the d.c. machine. The fields of the rotary and the d.c. machine are excited from a constant-voltage source of direct current. Diagrammatically, this scheme is illustrated in Fig. 190.

In starting from rest, the secondary of the main motor A is connected to a resistor, which is gradually short-circuited by means of magnetic contactors in the usual manner. After the main motor has been brought up to speed, its secondary is transferred to the rotary converter.

The voltage on the d.c. side of the rotary is changed by varying the field of the d.c. machine B. This changes the voltage impressed on the secondary motor A, which changes the speed of this motor. At the same

[1] *Trans. A.I.E.E.*, Vol. 39, Pt. II, pp. 1135 ff.

time, the change in voltage on the rotary changes the speed of the rotary. These two actions take place simultaneously. The a.c. side of the rotary is connected to the secondary of the main motor *A*. Therefore, the frequency in the two machines remains the same and the change in speed takes place simultaneously.

To reduce the speed of the main motor, the field of the d.c. machine *B* is increased. This causes an increased voltage to be applied to the secondary of the main motor through the rotary converter, which in turn reduces the load current or may momentarily reverse this current. The main motor will then slow down until the sum of the generated voltage and the supplied voltage in its secondary is enough less than the ratio of transformation to cause full-load current to flow through the secondary. The reduction in speed, in turn, reduces the voltage of the d.c. machine so that a balance running speed is soon reached. The speed is increased by reducing the strength of the d.c. motor field. The power represented by the difference between full speed and actual speed is converted into work through the rotary converter and the d.c. machine, causing this machine to give a torque, which adds to or subtracts from the torque of the main motor *A*. If the set is running at 75 per cent of normal speed, the main motor will be delivering 75 per cent of its rated output and 25 per cent will be delivered by the d.c. machine. The torque of the main motor remains constant, as this is fixed by the excitation of the primary and the design characteristics of the machine, both of which remain constant. The d.c. motor, however, increases its torque as the speed of the main motor decreases. When the main motor *A* is operated above synchronous speed, the torque of the d.c. machine *B* is subtracted from the torque of *A*. The torque delivered by the d.c. machine is directly proportional to the change in speed of the main motor, so that the horsepower output of the combined unit remains practically constant.

The power factor of the main motor can be altered by changing the excitation of the rotary fields. In this way the power factor of the motor may be increased so that it is above 90 per cent, but ordinarily a leading power factor is not obtained.

This method can be used to operate the main motor above synchronism as well as below synchronism. If operation at normal speed is desired, the regulating set can be disconnected and the secondary of the main motor can be short-circuited.

Method II.—This method is similiar to Method I, except that for the d.c. machine coupled to the main motor a motor-generator set, not coupled, is substituted. The scheme of connections is shown in Fig. 191. The operation is very similar. The rotary converter *C* supplies power to the d.c. machine *B*, which drives the a.c. machine *D* and returns power to the line. The speed of the main motor is adjusted by changing the field

strength of the d.c. machine *B*. The difference between these two schemes is that, in the first method, power is converted into mechanical work and returned to the main-motor shaft. This gives a constant horsepower throughout the range of the equipment. In Method II, power is returned to the line. The main motor operates at constant torque, but the horsepower decreases with the speed. The power returned to the line is the difference between the horsepower that the motor would deliver at full speed and the horsepower that it actually delivers at the reduced speed. In both methods, the losses are very small and most of this difference in power is saved. By reversing the polarity of the power supplied to the secondary of the a.c. motor, it may be made to operate above synchronism. This may be accomplished in several ways; the additional power in this case will be taken from the line by the motor-generator set.

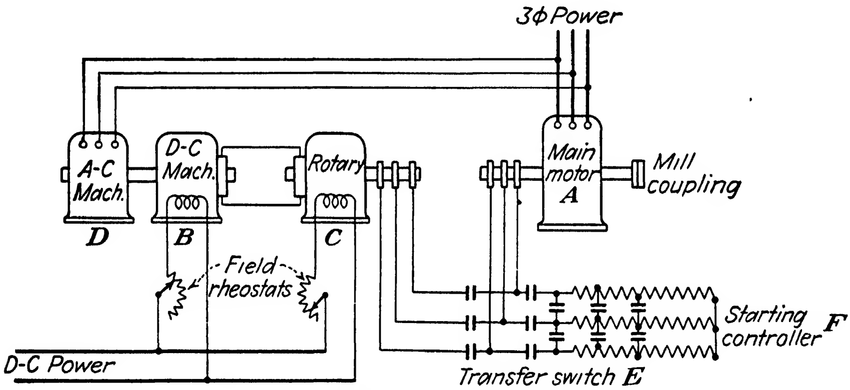


FIG. 191.—Method II, constant torque.

Method III.—This equipment (see Fig. 192) consists of a main driving motor *A*, having mounted on its shaft a small frequency changer *D*. Separate from this main motor is a set consisting of an a.c. induction or synchronous machine *C* coupled to an a.c. commutator machine *B*. The a.c. commutator machine *B* is operated at nearly constant speed by the a.c. machine *C*, to which it is coupled. The field strength of this commutator machine is varied in order to supply different voltages to the secondary of the main motor. The method of varying this field consists in connecting one end of each field coil to an autotransformer, in the secondary of the main motor. The other end of each field coil is connected through a resistance to the low-frequency, or commutator, end of the frequency changer *D*, mounted on the main-motor shaft. The frequency changer is so connected that, when the main motor is operated at synchronous speed, the commutator end of the frequency changer supplies direct current. At any other speed of the main motor, an alternating

current is supplied to the field, which has the same frequency as the secondary of the main motor. This can be better understood by referring to Fig. 193. When the main motor is operating below synchronism,

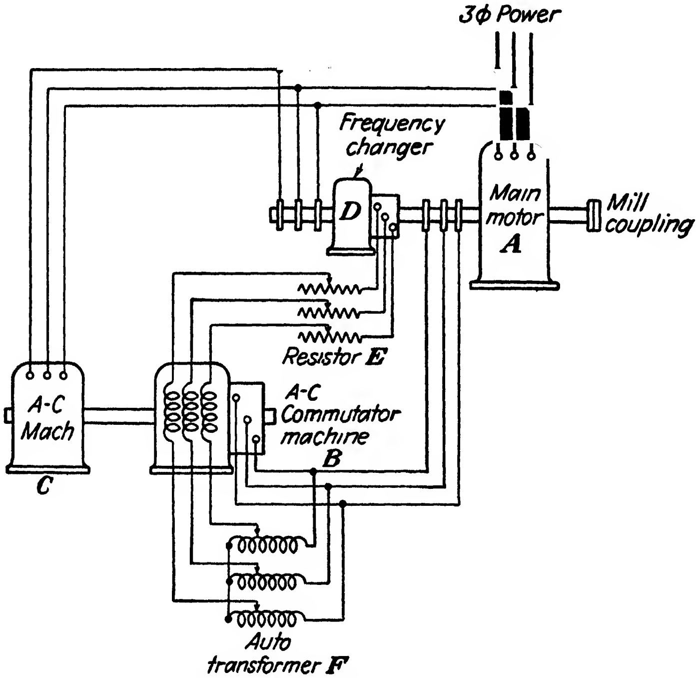


FIG. 192.—Method III, constant torque

we can let the line AB represent the frequency due to the rotation of the a.c. field, and the line BC the frequency due to the rotation of the frequency-changer armature, which is coupled to the main machine A and

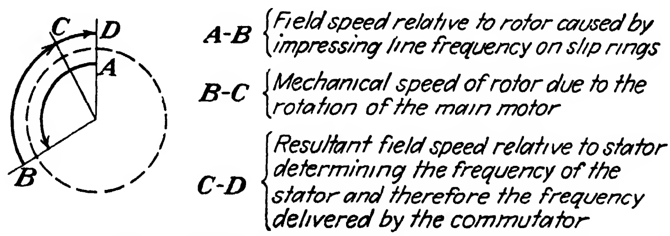


FIG. 193.—Analysis of frequencies in frequency changer.

rotates at the same speed as that machine. The line CD will then represent the difference in these frequencies and will be the frequency that is delivered at the commutator end of the frequency changer. Since this frequency is equal to the difference between synchronous speed and the

actual speed of the main motor, it will be the same as the frequency in the secondary of the main motor for all speeds of the main motor.

Since the field of the commutating machine *B* is excited by two sources of power out of phase with each other and independently adjustable (phase relation of the frequency changer by shifting the brushes; current from the frequency changer by varying the resistor; and voltage from the auxiliary commutator circuit by adjusting the autotransformer), both the phase relation and the strength of the excitation can be controlled. This adjusts the phase and the amount of voltage impressed on the slip rings of the main motor *A* and provides a ready means for adjusting its speed and power factor. Motor *A* may be operated at a leading power factor when this is desired.

The speed of the main motor can be adjusted from below synchronism to above synchronism while it is operating under load. In order to pass through synchronism, the voltage impressed upon the secondary of the main motor must equal zero when the main motor is operating at about 3 per cent below synchronous speed, in order that there will be sufficient voltage to circulate the load current. When the main motor reaches synchronous speed, the frequency of the secondary circuit is zero and the voltage from the autotransformer *F* is zero; therefore, the commutating machine *B* is excited entirely from the frequency changer *D* on the main-motor shaft; the voltage supplied from machine *B* must now be sufficient to circulate the load current. This voltage is in the opposite direction to that impressed on the secondary below synchronism. The transition can be illustrated by Figs. 188 and 189. As the motor approaches synchronous speed (see Fig. 188), the line *BC* is reduced in length until it reaches zero. The line *EF* then equals *AB* and the voltage of machine *B* is zero. In order to obtain a further increase in speed, the voltage supplied by machine *B* is reversed, and the line *EF* reduces to zero and then reverses, as is shown in Fig. 189.

The torque of the main motor remains constant throughout the range and the horsepower varies directly with the speed. The difference in horsepower represented by a speed slower than synchronism is returned to the line through the commutator machine and the induction machine that it drives. When it is operating above synchronism, the extra power is obtained from the line through the synchronous, or induction, machine to the commutator machine and then to the main motor. The power input to the primary and the torque of the main motor remains the same for all speeds, the horsepower varying with the speed.

Method IV.—This method is the same as the Method III, except that the commutator machine *B* is coupled to the main-motor shaft instead of being driven by a separate a.c. machine. The scheme is illustrated diagrammatically in Fig. 194. The energy represented by the difference in

speed is converted into work by the a.c. commutator machine B, which either adds to or subtracts from the torque of the main motor A, depend-

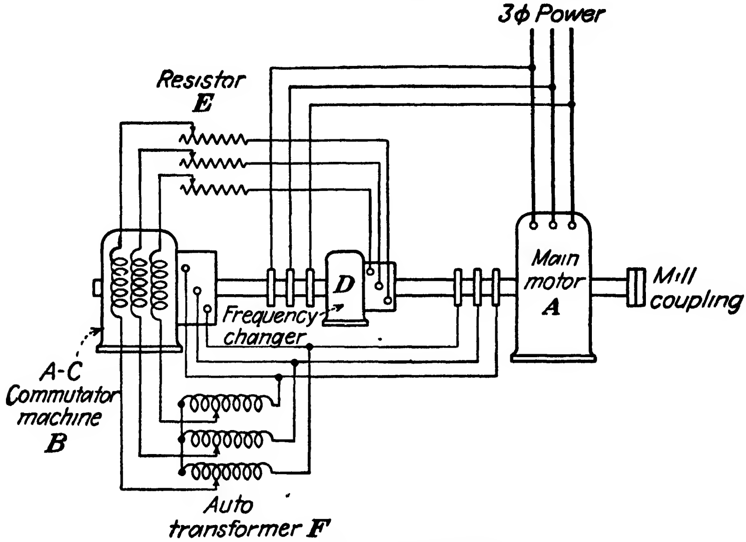


FIG. 194.—Method IV, constant hp.

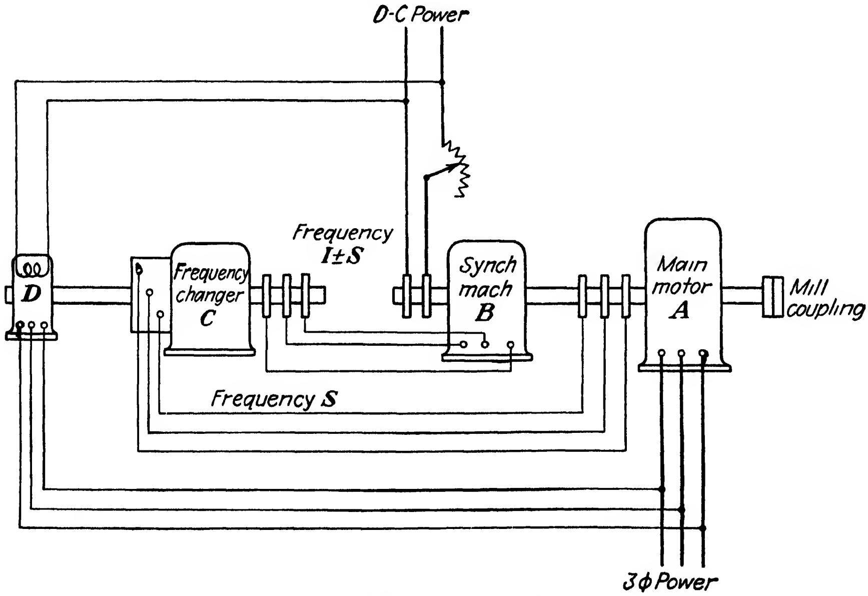


FIG. 195.—Method V, constant hp.

ing on whether the set is operating below or above synchronism. The equipment, therefore, operates on a constant-horsepower basis, no energy being returned to the line.

Method V.—The main driving motor A has a synchronous machine B coupled to the same shaft. Mounted separately is a frequency changer C, driven by a small synchronous motor. The diagram of connections is shown in Fig. 195. The secondary of the main motor is connected to the commutator end of the frequency changer. The slip-ring side of the frequency changer is connected to the synchronous machine on the main-motor shaft. The d.c. field of this synchronous machine B can be varied by means of the field rheostat.

The frequency changer runs at a constant speed corresponding to the synchronous speed of the line. The synchronous machine coupled to the main motor operates at a speed greater or less than synchronism, corresponding to the slip of the main motor. If we represent the slip of the main motor by S, then the frequency of the synchronous machine is equal to 1 plus or minus S. This frequency is imposed upon the slip-ring side of the frequency changer, which in turn delivers a frequency equal to the slip in the secondary of the main motor, on account of the frequency changer operating at synchronous speed. This arrangement ensures that the frequency of power supplied to the main motor is of the correct value.

The voltage delivered by the synchronous machine coupled to the main motor is adjusted by changing the strength of the d.c. field. This voltage is transmitted through the frequency changer to the secondary of the main motor, which rotates at the proper speed to develop a voltage sufficiently above or below that supplied by the frequency changer to circulate the load current (see Figs. 188 and 189). By adjustment of the value and the direction of the voltage of the synchronous machine, the main motor may be operated either above or below synchronism at any speed within the range of the equipment.

The power factor of the main motor may be adjusted either by shifting the brushes on the commutator end of the frequency changer or by shifting the poles in the synchronous motor D, driving this machine. This motor is very small compared with the frequency changer, as it has only to overcome the friction and windage losses; therefore, the poles can be shifted economically by winding the field coils in sections and connecting them to a small rheostat.

The power taken from the supply lines remains constant. The difference in power delivered by the main motor, owing to a reduction in speed, is converted into mechanical energy by the synchronous machine, coupled to the motor shaft. In this way a constant horsepower is delivered to the mill coupling at all speeds.

Method VI.—This method (see Fig. 196) uses a frequency changer having a wound stator and a rotor with a commutator on one end and slip rings on the other end. The commutator end is connected to the slip rings of the main motor and the slip-ring end to the line, through an auto-

transformer. The speed of rotation of the frequency changer is controlled by changing the resistance in the stator winding. Its performance is similar to a wound-rotor induction motor, the slip rings supplying energy to the rotor, which in this case is the primary member, the stator being the secondary. The amount of slip, or speed, is fixed by the resistance in the secondary circuit.

Another method would be to excite the stator from the commutator end of the frequency changer and change the speed by a resistance in this circuit.

The voltage supplied to the secondary of the main motor depends upon the voltage imposed on the slip rings of the frequency changer by the

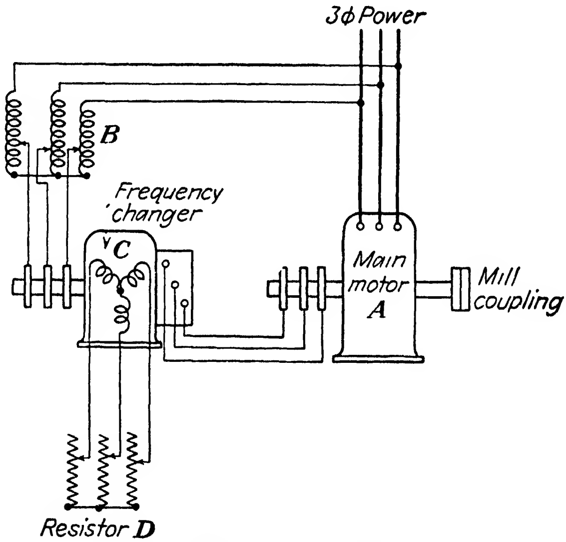


FIG. 196.—Method VI, constant torque

autotransformer B; at the same time the speed at which the frequency changer operates must be adjusted to maintain its secondary frequency the same as that of the main-motor secondary. When it is operating above synchronism, energy is taken from the line.

A modification of this method consists in coupling the frequency changer C to the shaft of the motor A and omitting the stator windings. The frequency changer in this case operates exactly the same way as the machine D in Fig. 192, Method III, with the exception that in Method III this machine furnishes power to the fields of the a.c. commutator machine B, while in Fig. 192 the frequency changer C would supply the power directly to the secondary of the main motor A. In the latter case, the frequency changer must be large enough to supply the power represented by the difference in speed required either above or below normal

speed of the main motor A. The speed is fixed by that of the main motor A, which is usually quite slow, so that the frequency changer might be quite large and expensive. The arrangement, however, is very simple and can be easily operated through synchronism, stable operation being obtained at all speeds.

These methods of control of wound-rotor induction motors were first developed for large motors, used for driving the main rolls in steel mills. There are two general methods of rolling steel. One consists in passing the metal back and forth through one set of rolls; and the other method uses a number of sets of rolls, the metal passing continuously from one set to the next. This latter is known as a "continuous mill." Where a single stand of rolls is used, two rolls only may be employed, the motion of the metal back and forth being obtained by reversing these rolls. When this method of rolling steel is used, the driving motor must be reversed

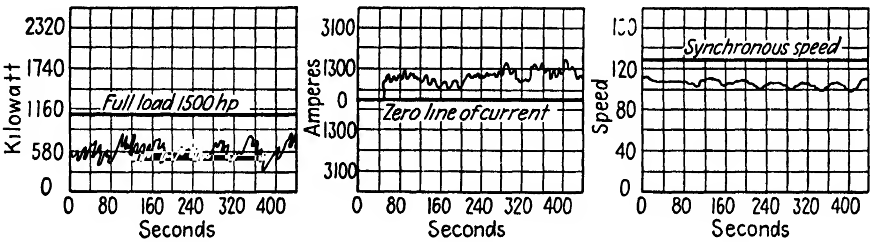


FIG. 197.—Characteristic curves of a 1,500-hp. constant-horsepower adjustable-speed set.

quickly and frequently; therefore, d.c. motors are used with the voltage method of control described in Chap. XI.

If three rolls are used and the metal passes one way between the bottom pair and then back between the upper pair, the rotation is continuous in this direction and the a.c. motor can be used. The speed of this motor may be adjusted by any one of the methods described above. In most cases, the speed is adjusted for a particular class of work and is not changed between passes. The speed is adjusted when rolling begins and remains fixed until the class of work is changed. In most cases, it is not necessary to adjust the speed under load, which simplifies the controller.

When the continuous process of rolling steel is used, the roughing rolls, or those through which the steel is passed first, are often driven at a constant speed by an a.c. motor and only the finishing rolls are provided with adjustable-speed a.c. motors.

The speed regulation of a.c. motors between no load and full load can be made very close, the difference being due to the voltage required to circulate the load current. In some cases, the load varies over a considerable range and it is desirable to provide a flywheel to absorb the peak load. In order to have this fly wheel effective, it is necessary for the motor to

drop in speed when the load comes on. This result can be obtained either by increasing the resistance in the path of the load current or else by designing the regulating machine to have the proper characteristics to give

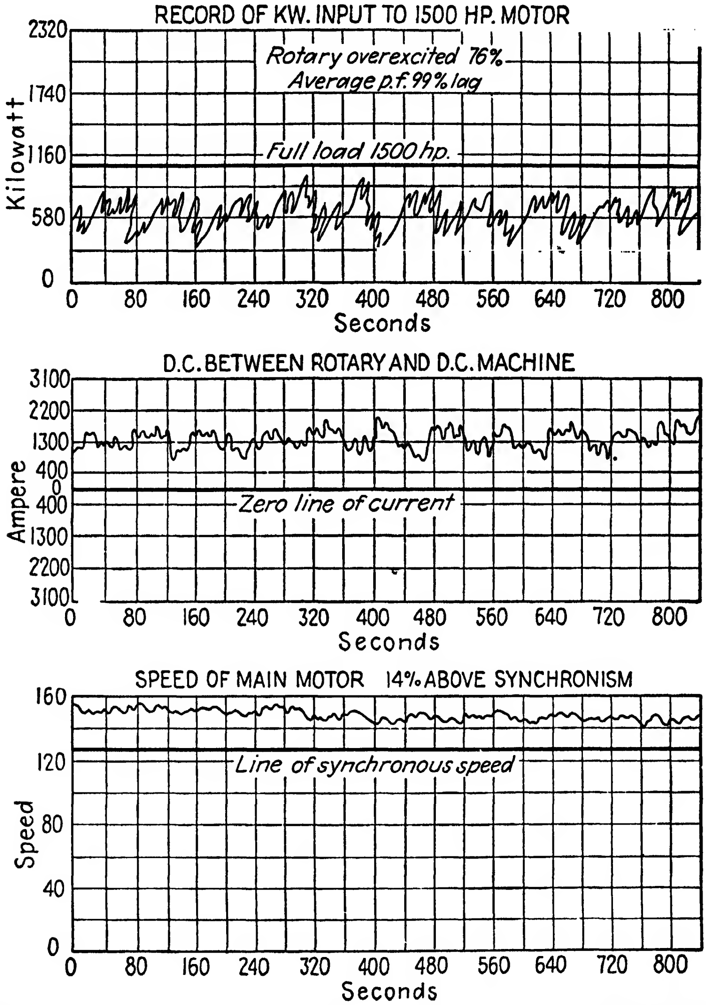


FIG. 198.—Characteristic curves of 1,500-hp. constant-horsepower adjustable-speed set operating at 14 per cent above synchronism.

this result. The curves in Figs. 197 and 198 show the speed variations of one of these adjustable sets operating below and above synchronism.

Electric motors have almost entirely replaced steam engines for rolling steel where new equipments are installed. The curves in Fig. 199 show this increase in total horsepower over a period of years. The

efficiency and the flexibility of the electric drive has made an entire change in engineering practice. The slow-speed reciprocating engine has been supplanted by the high-speed turbine. Steam as a prime mover is used

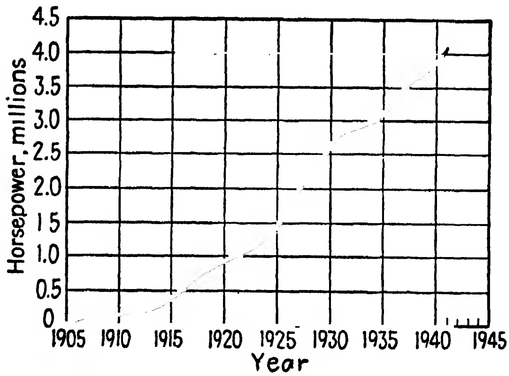


FIG. 199.—The cumulative curve of main-drive motors over 300 hp. shows a 1942 total of 4,045,665 hp. This curve is typical of the increased use of electric drive in industry. (*From Iron Steel Engr. Year Book*, 1942, p. 35.)

now almost exclusively for the development of electric energy, which in turn is applied to the work by means of the motor. The application to steel mills is only one illustration of this change.

CHAPTER XIV

RESISTORS[1]

TYPES OF RESISTORS

The most common form of resistor is the cast-iron grid, shown in Figs. 200 to 202. Cast iron is admirably adapted for this purpose on account of its cheapness, high electrical resistance, freedom from corrosion, and small temperature coefficient. The resistance of cast iron increases about 15 per cent with a change of temperature of about 250°. Its principal limitation is that it is not suitable for small apparatus where a large ohmic value is required with a small capacity, requiring high-resistance units of small size.

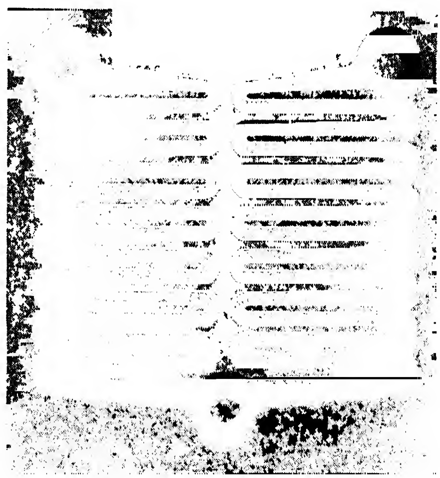


Fig. 200.—Cast-iron grid resistor unit

Where a large ohmic value is required in a small space, the embedded type of resistor is used. It is made in various forms, the resistance material usually consisting of a wire or ribbon embedded in enamel or in some similar compound, as in Fig. 203. It is also common to make up units in the form of plates. Embedding the resistance material gives increased thermal capacity and mechanical protection. It also prevents conducting material, such as metal dust, from collecting on the unit and reducing the resistance. Most of these embedded units can be heated to destruction without any external flash or drippings.

Cast Grid Resistors.—These grids (see Figs. 200 to 202) are cast from iron or from an iron alloy; they may be in several sizes for different ratings; they usually have two widths of boss, which controls the spacing

[1] A "resistor" is "An aggregation of one or more units possessing the property of resistance, used in an electric circuit for the purpose of operation, protection, or control of that circuit." This term was coined to express properly the part of a controller often referred to as the "resistance." The word "resistance" expresses the property of a substance and should not be used to denote the material itself.

between grids. Alloy grids will stand more mechanical shock and can be given greater ohmic value, but they cost more. The ohmic value is changed by using different cross sections of the grid loops, as well as by using alloys.

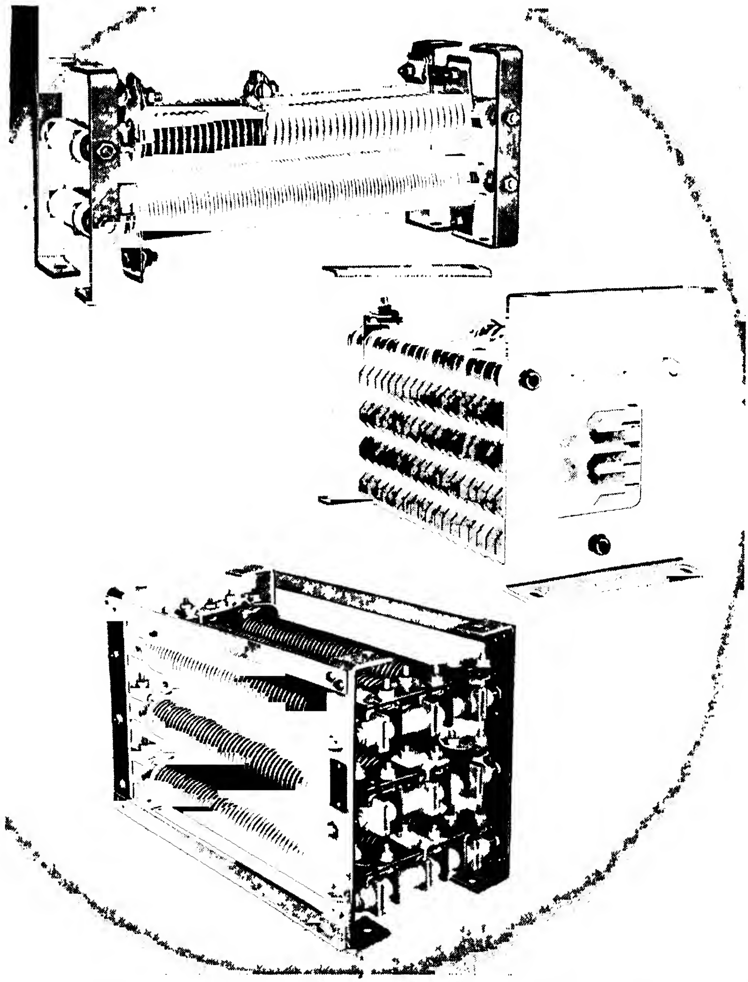


FIG 201 —Grid and edge-wound resistors (*Courtesy of Westinghouse Electric & Manufacturing Company*)

The grids are threaded on insulated tie rods attached to end frames. The contact between grid bosses is by pressure from the tie rods; mica washers are used to insulate between grids to give the current a zigzag path. Metal terminals, usually with slotted ends, are inserted between grids and make pressure contact with the grid boss. The slots permit a

terminal to be relocated or additional ones to be added by slacking off the tie-rod pressure. Grids are usually given a coating of aluminum paint.

Edge-wound Ribbon Resistors.—Ribbon resistors (see Fig. 201) occupy a position midway between cast grids and wire-wound tubes.

FIG. 202.—Grid type resistor. (*Courtesy of General Electric Company.*)

They can be furnished with higher ohmic resistance than can grid resistors, and have greater ampere capacity than do wire-wound tubes. They will stand greater mechanical shock than alloy grids and are suitable for some applications where grids would be broken. They have greater

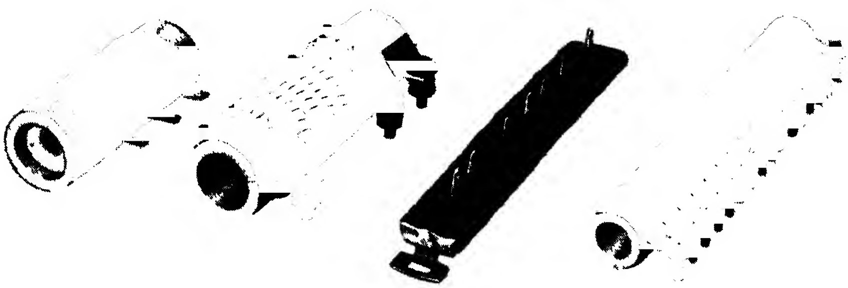


FIG. 203.—Vitrohm wire-wound resistors. (*Courtesy of Ward Leonard Electric Company.*)

continuous rating and less short-time rating than have grid resistors of comparable size.

The ribbon is wound edgewise, in a spiral, and is screwed on porcelain insulators or is wound edgewise in loops between porcelain blocks. It may also take other special forms. The ribbon material can be stainless steel, Nichrome, or a copper-nickel steel alloy; any suitable metal may

be used to give a wide range of ohmic values. The units are assembled in end frames, similar to grid resistors.

Wire-wound Resistors.—The wire is wound on a clay or porcelain base and is embedded in a surface coat of baked enamel. It is usually in the form of a tube or a plate. The embedding is desirable to protect the fine wire from corrosion and mechanical damage; the covering greatly increases the thermal capacity of the resistor and prevents the wire from creeping out of place when it is hot. Skill and long experience are required for making good embedded resistors.

Heavy wire is sometimes wound on an asbestos-insulated tube or some other shape and is covered with a special cement. Many different types of wire-wound resistors have been made, some of which are not very satisfactory. This type of resistor gives a high ohmic value in a small

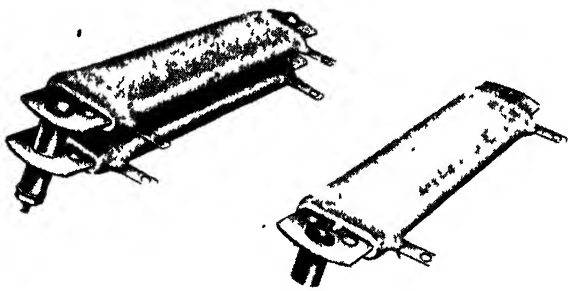
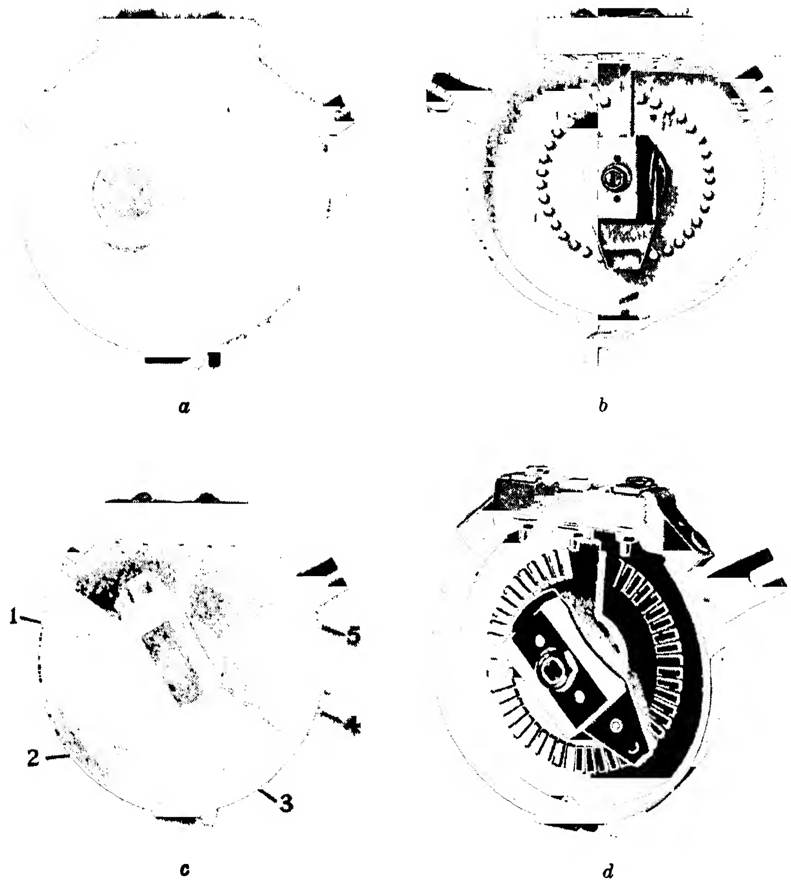


FIG. 204.—Vitrohm strip-type resistors. (*Courtesy of Ward Leonard Electric Company.*)

space and can have many taps. Wire made from different alloys suitable for this purpose is available. The capacity depends upon the outside surface area. The mounting can be made to suit the application.

Resistors of the Compression Type.—Some rheostats and controllers have resistors composed of graphite disks. The change in ohms is obtained by changing the pressure on the column of the disks. These disks are illustrated in Fig. 216 and a rheostat of this type in Fig. 218. The change in ohms with pressure is shown in curve, Fig. 208. If a rheostat were designed so that the pressure on the column was changed in a uniform manner, the resistance would not be altered so as to give the best starting or regulating conditions. In order to improve this condition, a cam is used for compressing the resistance column. This cam acts through a spring and is so designed that equal movements of the controller handle give approximately equal changes in resistance. The curve in Fig. 208 shows the change in resistance with the movements of the controller handle. Controllers using this form of resistor are shown in Figs. 218, 255, and 256.



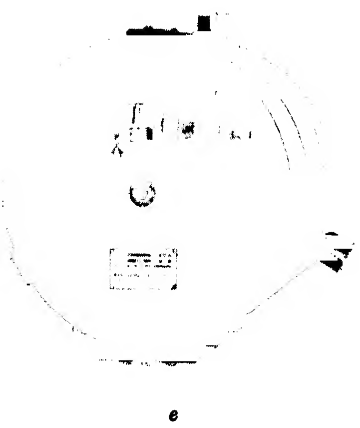
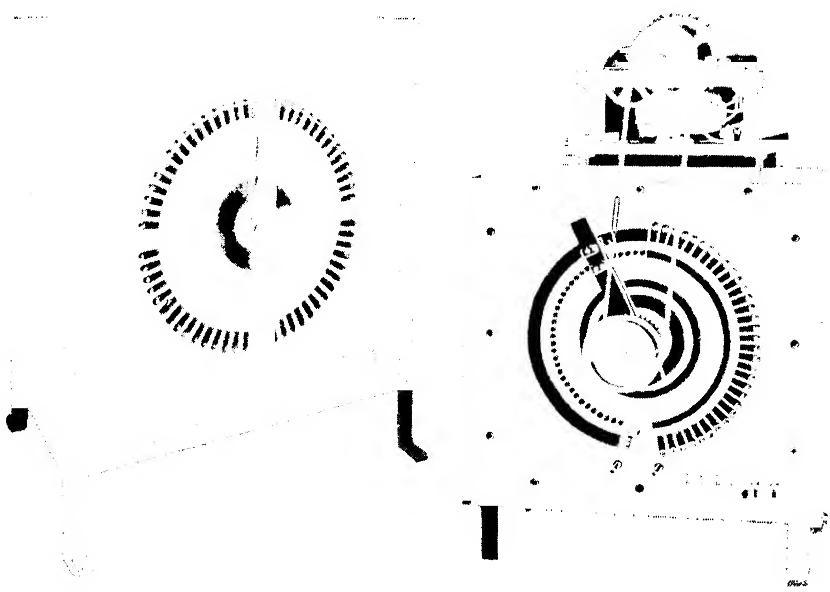


FIG. 205.—Front-of-board Vitrohm field rheostat: *a*, front view; *b*, rear view. *c*, Shows stages of manufacture· (1) Pressed-steel plate forms a rigid base. After the entire surface is (2) sand-blasted to remove foreign particles, the (3) ground coat of enamel is applied which protects the surface of the plate and forms an electrical-insulating heat-conducting surface upon which to mount the (4) resistance element of alloy wire. To these wires the heavy contacts are fastened; this gives a mechanically and electrically perfect joint. (5) Vitrohm insulation is applied over the resistance wire. It holds the wire and contacts securely and protects them against corrosion and mechanical inquiry. *d*, Vitrohm field rheostat with small rectangular contacts. *e*, Motor-operated Vitrohm field rheostat that is used with a reversing planer control. (*Courtesy of Ward Leonard Electric Company.*)



a *b*

Fig 206 *a* Ribohm field rheostat single-face plate front view *b* Motor-operated Ribohm rheostat combining a generator-field rheostat and a motor field rheostat

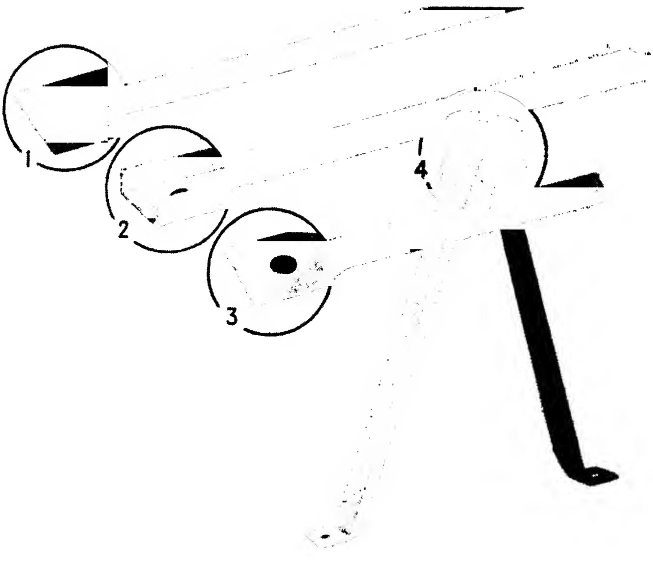
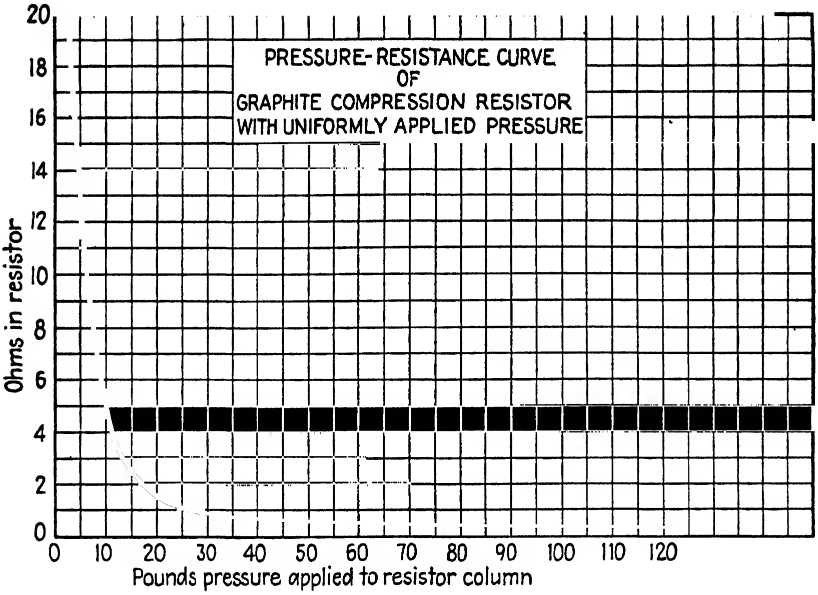


Fig 207 —(1) A metal ribbon of suitable size and alloy (2) is punched and formed into a channel and (3) after being flattened at the ends and center (4) is bent into a V shape This construction possesses the advantages of light weight rigidity and strength Resistor used in Fig 206 (*Courtesy of Ward Leonard Electric Company*)



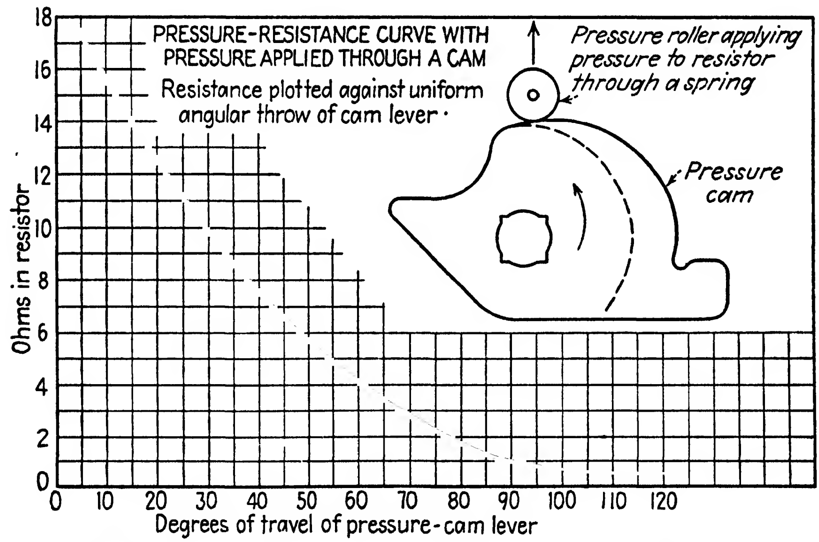


Fig. 208.—Pressure-resistance curve of graphite-compression resistor. This curve shows the relation between the resistance of the carbon pile and a uniformly increased pressure applied to the column. When used in apparatus requiring a uniform decrease in resistance with a uniform travel of the controlling lever, the increments of pressure should not be uniform, but should be carried through suitable cams and springs as shown in the lower curve.

A rheostat is defined as a resistor provided with means for varying its resistance. This usually takes the form of a series of contacts mounted on the surface of an insulating material having an arm arranged for making connection between a central post, which forms the pivot of the arm, and the various contacts, which are arranged in a circle. Mounted back of this face plate is a series of resistor units, as shown in Fig. 219. For small sizes, the contacts and resistance material are both embedded in a

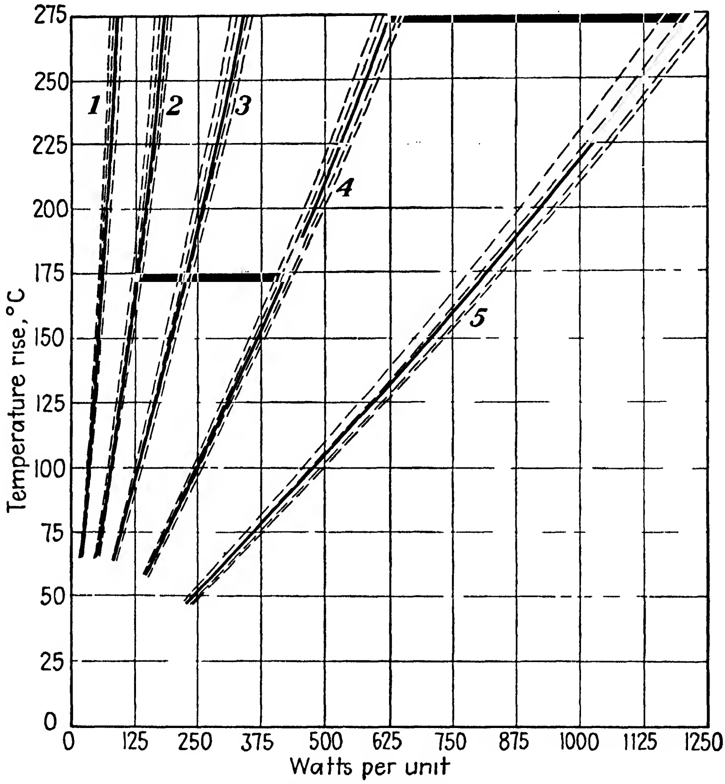


FIG. 209.—Relation of the temperature use and the energy loss per resistor unit for five different classes of service.

compound, forming a complete unit, known as a "plate-type rheostat" (see Fig. 205).

In applying resistors, two points should be considered: (1) the ability to radiate and conduct the heat from the unit to the surrounding atmosphere, (2) the ability to absorb heat. Usually the mass of the resistor is small compared with that of a motor or controller for dissipating the same amount of heat energy, so the energy absorbed by the resistor will raise its temperature more rapidly. When the resistor is used for starting purposes only, the absorption forms a very important item in the design.

For intermittent duty, radiation is the controlling feature. The relation between temperature rise in degrees C. and the watts per unit for five different conditions of operation is shown in Fig. 209. The heavy line is the average value and the dotted lines on either side represent the variations due to the different cross sections of the grids used. These curves, of course, apply only to one particular size of grid and are shown for the purpose of illustrating the effect that different classes of service have upon the capacity of a resistor of a given size. Curve 1 is for con-

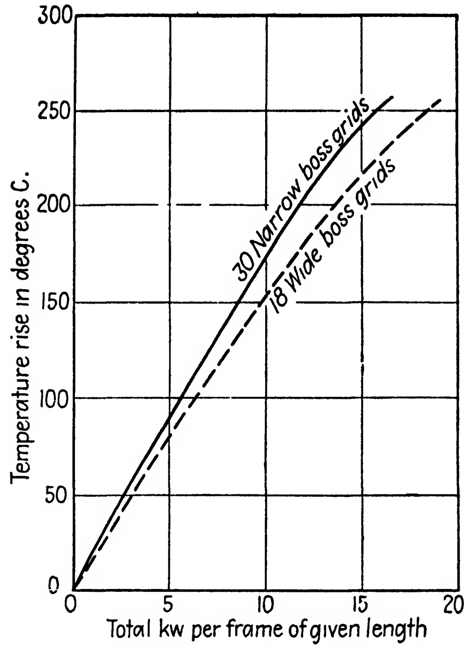


FIG. 210.—Comparative radiating capacity of the same size resistor frames using different spacings of grids.

tinuous service; curve 2, for a cycle of duty, in which the resistor is in circuit for 2 min. out of every 4 min., with 2 min. of rest between. Curve 3 represents a duty cycle of an ordinary shop crane of 1-min. service and 3 min. of rest. Curve 4 represents a duty of 30 sec. with 3 to 5 min. of rest. Curve 5 is a duty of 15 sec. in each 4 min. Curve 5 corresponds to ordinary starting duty. In making these tests, it was found that the spacing between the grids was an important factor and preliminary tests were made to determine the most economical spacing. Similar data should be obtained for any form of resistor used, so that an intelligent application can be made.

The effect that the spacing of the grids has upon their radiating capacity is shown in Fig. 212. Standard grids were used and the spacing

between the grids was changed by introducing washers. Curve *a* shows the minimum spacing. Curve *b* shows the effect of increasing this spacing by ¼ in. Curve *c* shows the effect of increasing it by ⅜ in. Further tests were made by increasing the spacing ½ in., but the results were practically the same as with the ⅜ in. increased spacing, showing that the economical limit had been reached for that particular design. The curves show very clearly the increase in capacity with a rise in temperature. Where the grids are spaced close together, the increase in capacity per degree rise of temperature is less than for the wider spacing. The

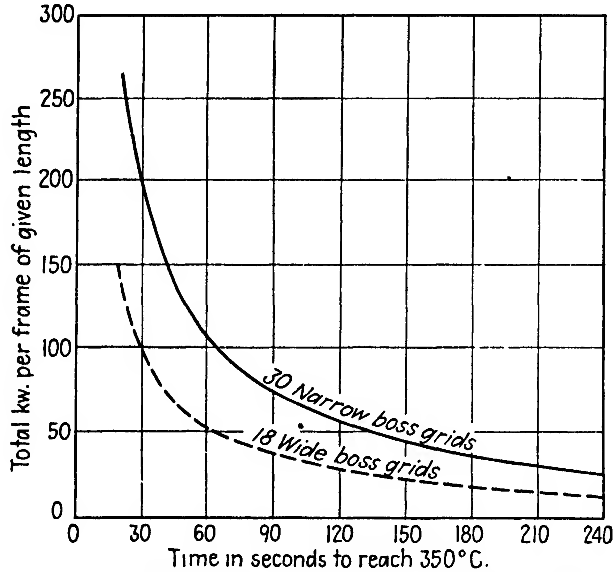


FIG. 211. Comparative heat absorption of two resistor frames of the same length having different number of grids.

tests show that if the resistor is used for continuous or intermittent duty, considerable material can be saved by a proper spacing of the grids.

The economical arrangement of the grids is more clearly shown in Fig. 210. The duty cycle is for light intermittent duty. The solid-line curve was obtained from a frame of 30 grids with narrow bosses, and the dotted-line curve from a frame of 18 grids with wide bosses. The frame was of the same length in both cases. The curves indicate that the frame of wide-boss grids radiated more energy than the one with narrow-boss grids. It is therefore a better frame, costs less, and is lighter in weight. The same relation could be shown if similar curves were plotted for heavy starting duty and heavy intermittent duty.

For light starting duty the time cycle is so short that most of the energy is absorbed by the resistor material itself, and radiation has less

effect. Therefore, the grids for this duty are spaced much closer together and the capacity is determined largely by the weight of the material and less by the radiation. From a heat-absorption standpoint, for light starting duty, the narrow-boss grids are better, as is shown in Fig. 211.

In the designing of resistors, certain arbitrary assumptions must be made, as it is manifestly impossible to predetermine the exact cycle of operation for many applications. The National Board of Fire Underwriters has adopted tests for starting rheostats that have proved very satisfactory for general-purpose starters. They are based on the average

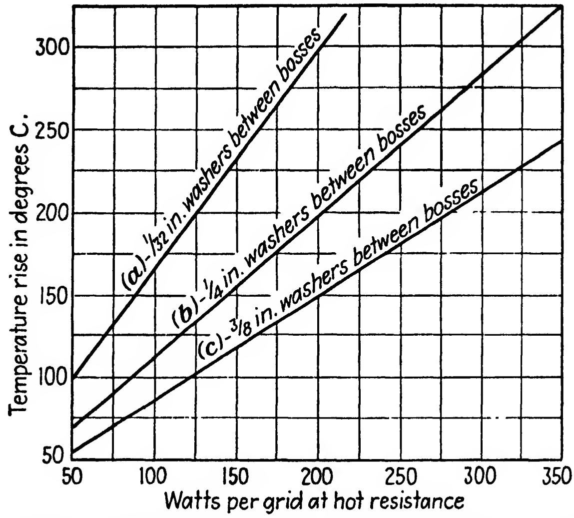


FIG. 212.—Relation between the spacing of cast-iron grids and temperature rise.

operating conditions that must be met when the motor is started, and provide a sufficient factor of safety to give protection against fire hazard. Where the rheostat is used for speed regulation, its design is a simple matter if the load is known. Ordinarily, the requirements may be grouped as to duty into two classes—one known as "constant torque," where it is assumed that the current remains practically constant throughout the entire speed range and is equivalent to the full-load motor current, and another known as "fan" duty, where it is assumed that the current is approximately proportional to the speed of the motor.

The more difficult applications are for intermittent duty, such as crane service. The general-purpose crane used in an ordinary machine shop or foundry operates over a wide range of load and for varying intervals of time. An early analysis of this problem caused manufacturers to rate their resistors on the basis of different loads for different time intervals, assuming that if a heavy load were being lifted it would occur seldom and the time interval, therefore, could be made relatively short. The

TABLE 2.—RESISTOR CLASSIFICATION TABLE

Adopted by the National Electrical Manufacturers Association, Jan. 29, 1937

Approx. per cent full load current on first point	Starting torque in per cent of full-load torque					Resistor classification numbers applying to duty cycles							
	D.-c. motors			A.-c. motors wound motor		30 sec. on out of each 15 min.	5 sec. on out of each 80 sec	10 sec. on out of each 80 sec.	15 sec. on out of each 90 sec.	15 sec. on out of each 60 sec.	15 sec. on out of each 45 sec.	15 sec. on out of each 30 sec.	Continuous duty
	Series	Compound	Shunt	1-phase[1] starting	3-phase[1] starting								
25	8	12	25	15	101	101	111	131	141	151	161	171	91
50	30	40	50	30	50	102	112	132	142	152	162	172	92
70	50	60	70	40	70	103	113	133	143	153	163	173	93
100	100	100	100	55	100	104	114	134	144	154	164	174	94
150	170	160	150	85	150	105	115	135	145	155	165	175	95
200 or over	250	230	200		200	106	116	136	146	156	166	176	96

[1] This refers to the connections of the rotor circuit.

same resistor could be used for an average load operating for a longer period, etc. This method of rating became quite complicated and did not prove practical. An accumulation of data indicates that resistors for crane duty may be divided into two classes: those for general-purpose duty, and those for heavy duty, such as those needed in certain operations in steel mills.

Other applications may be similarly analyzed. In order to make it easy to express resistors in a definite way, The National Electrical Manufacturers Association adopted the resistor classification shown in Table 2. The horizontal lines classify the resistors according to the percentage of full-load motor current that is obtained when all of the resistor is in the circuit, and the vertical lines represent the service conditions.

The starting- and intermittent-duty resistors in the classification table are designed primarily for use with motors requiring an initial torque corresponding to the current value for the class of resistor specified and requiring a root mean square accelerating current not more than 125 per cent of the full-load motor current.

If the resistor is tested without its being connected to a motor, it should be connected to a line voltage that will give the initial current specified, and the steps should be cut out at equal intervals in the "time-on" period of the cycle specified; the current at no time during the cutting-out period should exceed 125 per cent of the rated value. This test should be repeated, at the intervals specified, for 1 hr. If resistors are desired for a longer time period than that shown in Table 2, the next higher class number to the right should be selected; if a higher starting torque is required, the next larger class number in the vertical column should be selected.

The amount of speed reduction obtained with a resistor in series with the armature or in the secondary of a slip-ring motor depends upon the load on the motor, and may be obtained from the following formula:

$$\begin{array}{c}\text{Speed reduction obtainable}\\\text{in per cent of full-}\\\text{load speed}\end{array} = \frac{\begin{array}{c}\text{actual load torque}\\\text{required in per cent}\\\text{of full load}\end{array}}{\begin{array}{c}\text{torque given in column}\\\text{under particular}\\\text{motor used}\end{array}} \times 100$$

For example, consider a wound-rotor motor with Class 95 resistor connected to a load requiring 70 per cent torque at slowest speed; this will give a speed reduction of

$$\frac{70}{150} \times 100 \text{ or } 47 \text{ per cent}$$

The current taken from the line during the starting period is less than would be obtained by dividing the effective voltage by the ohms resist-

ance. This reduction in current is caused by the inductive effect and the resistance in the lead wires and motor circuit. For the average application, the peak current during acceleration can be assumed as approximately two-thirds of the calculated value.

It is found in practice that the results obtained by different engineers agree very closely, so that the product of different manufacturing companies is on the same basis. The ordinary method of procedure is to divide the resistor into steps that follow a geometric progression. This can be worked out and tabulated for quick reference, as shown in Table 3.

TABLE 3.—METHOD OF PROPORTIONING STARTING RESISTORS, N.E.M.A. CLASS 135, FOR D.C. SHUNT AND A.C. WOUND-ROTOR MOTORS

	No. of steps	Step								
		1	2	3	4	5	6	7	8	9
Per cent ohms Per cent full-load amp	1	100 44								
Per cent ohms Per cent full-load amp	2	72 30	28 44							
Per cent ohms Per cent full-load amp	3	55 26	30 35	15 44						
Per cent ohms Per cent full-load amp	4	45 23	28 30	17 38	10 44					
Per cent ohms Per cent full-load amp	5	37 20	26 29	17 34	12 39	8 44				
Per cent ohms Per cent full-load amp	6	32 19	24 26	17 30	12 35	9 39	6 44			
Per cent ohms Per cent full-load amp	7	18 18	21 24	16 29	13 33	9.5 36	7 40	5.5 44		
Per cent ohms Per cent full-load amp	8	25 17	20 23	15 28	12 30	9.5 34	7.5 38	6.5 40	4.5 44	
Per cent ohms Per cent full-load amp	9	23 12	18 22	15 26	12 29	9 33	8 35	6 38	5 41	4 44

The method of calculating the ohms per step in a given resistance takes the form of a geometric series, —$R + RX_1 + RX_2 + RX_3$, etc., where R is the internal resistance of the motor and controller and X is the ratio of maximum and minimum accelerating current. The deriva-

tion of this formula can be obtained from textbooks on the subject or from electrical handbooks. The values obtained from such a formula are based entirely upon Ohm's law and do not take into account the effect of inductance in the circuit. The formula is sufficiently accurate, however, for most calculations.

The total number of ohms in a resistor is fixed by the classification number and the full-load current of the motor, and the number of sections of a resistor is determined by the steps on the controller, so that a designer can refer to the table, using the line corresponding to the steps in the resistor that he wishes to design, and then divide the resistor by

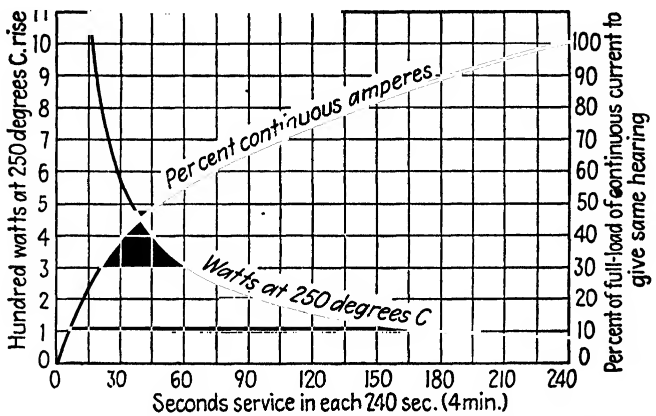


FIG. 213. Energy that can be dissipated in a grid for different lengths of service.

taking the proper percentage for each step as indicated by the table. This results in a uniform product's being obtained with respect to the total ohms in the resistor, and its subdivision into steps.

It is more difficult to determine the capacity for each resistor step. Data for this part of the design must be obtained from actual tests. A resistor radiates heat in proportion to the fourth power of its absolute temperature (Fig. 213). This means that an increase in the hot-spot temperature from 250 to 350° C. will materially increase the heat-dissipating ability of the resistor and, therefore, increase the factor of safety. Cast-iron grids show a dull-red heat at 600° C., which ordinarily will not damage the grids.

Unfortunately, this direct relation between temperature and radiating capacity is materially affected by the method of mounting and the circulation of the cooling air. If one cast-iron grid were located where there is a free circulation of air, this law would be followed very closely, but, as they are ordinarily manufactured, cast-iron grids are assembled in frames of from 20 to 30 grids. These frames, in turn, are mounted in boxes with

several other frames, so that the ultimate radiating capacity of the entire resistor depends upon the complete design.

The effect of increasing the time a grid resistor is in circuit is shown in Fig. 214. This curve was obtained by applying a definite load to the resistor for the time interval corresponding to each classification given in the table. The values plotted were the average hot-spot temperatures obtained. The actual temperature on test would first increase while the load was applied and then decrease during the off period. At first this difference in temperature was quite marked, but after the test was con-

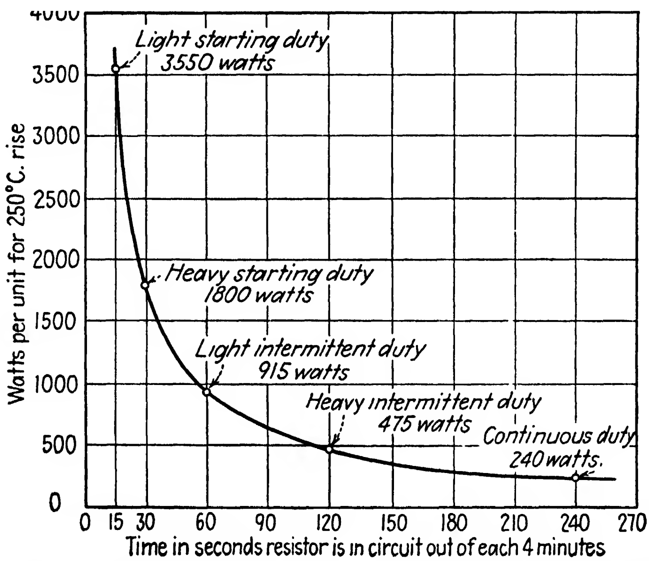


FIG. 214.—Relation between the time and the load required on a grid resistor to reach 250°C. use.

tinued for 1 hr., only a small variation was observed between the maximum and minimum temperatures, the average of which, therefore, was considered as representing the actual temperature of the resistor for that class of service. A number of tests had to be made to determine the amount of energy that would correspond to a 250° C. rise for each duty cycle. The curve shows that a resistor that has a continuous capacity of 240 watts will have 475 watts capacity on heavy intermittent duty, and still higher values for the other classifications.

With test data of this kind available, a curve can be plotted, as in Fig. 215, showing the relation between the length of time in seconds during which the resistor is in circuit out of each 4-min. period, and the percentage of continuous current to give equivalent heating. This last curve forms the basis of an actual resistor design. In Table 3, for each number

of resistor steps two values are given. One value is the percentage of total ohms in each step; the other is the percentage of full-load current that each step will carry continuously. In designing resistors, it is assumed that the first step of starting- and intermittent-duty resistors will be in circuit a smaller number of seconds than the last step. This

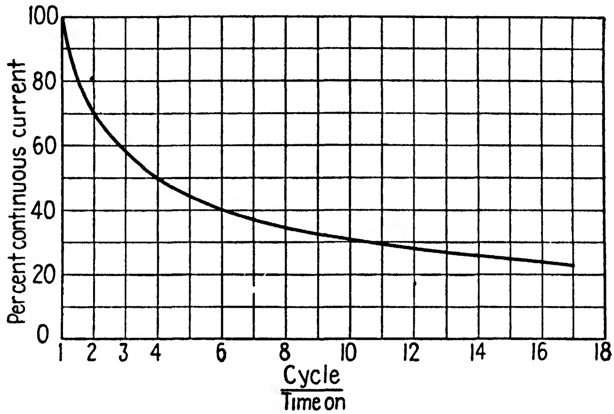


FIG. 215.—Relation between continuous and intermittent duty for various time cycles. Values are plotted for one particular size of resistor and are based on a temperature rise of 250°C.

gives a tapered capacity, so that the percentage of full load that the grid is capable of carrying should be smallest on the first step and increase with each step up to the last. It will be noted from Table 3 that on the first step of a three-step resistor the current is 26 per cent of the full-load current and on the other steps, 35 to 44 per cent, the intermediate steps being tapered.

All the foregoing data were taken from one particular design and are not applicable to any other design. They are given because they show clearly the relation that exists between the temperature of the grid and the current passing through the grid for different conditions, and they serve to illustrate how the design problem is worked out in practice. A different table is required for each size and type of resistor unit, and a different table for each resistor classification. For each ohmic value of grid of the same design it will be found that there is a slight variation in the watts per unit between the high and the low ohmic values, but

FIG. 216.—Parts of a Bradleyunit compression disk resistor. Graphite disks, insulated steel tube, end plug, and pressure plug. *(Courtesy of Allen-Bradley Company.)*

this difference is not very great, and it is sufficiently accurate to use an average value.

As has been previously explained, the arrangement of the units in the resistor box or frame is determined by test. This also applies to the grouping of resistor frames; *i.e.*, for light starting duty the resistors can be grouped close together, but for intermittent and continuous duty a greater

FIG. 217.—Rear view of wall-mounted starter, showing Bradleyunits, starting lever, and pressure equalizer assembly. Smooth motor acceleration is obtained. (*Courtesy of Allen-Bradley Company.*)

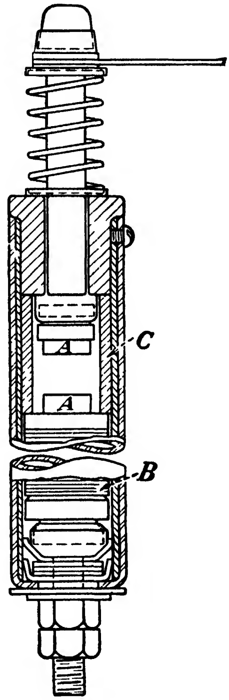


FIG. 218.—Resistor element for Fig. 217 starter. The first motion of the operating handle closes the contacts *AA*; a further motion compresses the disk *B* of the resistor element. The insulating tube *C* is made of arc-resistant quartz, and the vaporized quartz has an arc-quenching effect when the contacts are opened.

space is required. The total energy dissipated in starting small motors is not great and the arrangement of the frames is simple. Where large motors are used, it is desirable not to stack the resistor frames more than three high, and considerable space should be left between tiers of frames. Care should be taken to ensure a free circulation of air around all the resistor frames. Their capacity will be materially limited if they are located in the corner of a room or protected by partitions in such a way that the circulation of air is restricted. In arranging the grids in tiers,

the frames should be located in such a way that the heat will be distributed equally among the tiers.

Each application for controllers must be studied and the classification of resistor should be selected after the operating data are obtained. The same classification of resistor may not be equally well adapted for the same type of service in different mills and industrial establishments. It is, therefore, difficult to give a definite classification for every application.

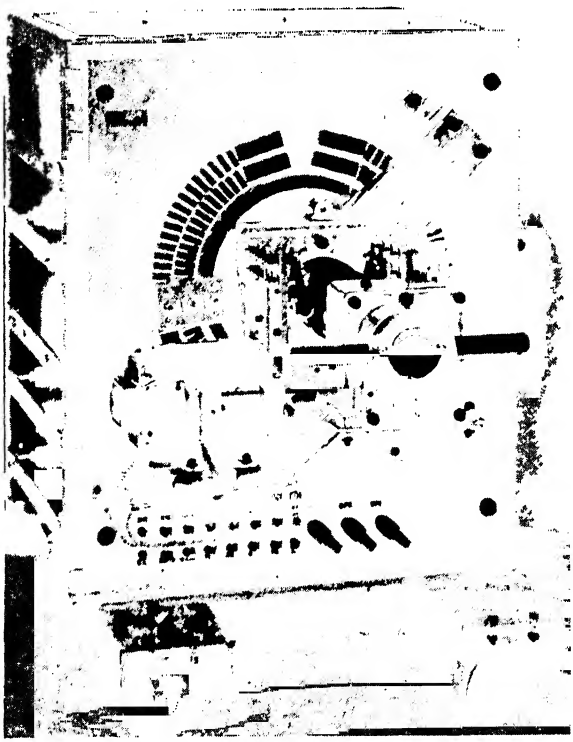


FIG. 219 —Westinghouse motor-operated rheostat.

Any engineer having occasion to select control equipment for a particular application realizes the importance of such data. The manufacturer of the control equipment may not have actual test data available for the particular application and, therefore, must use the average data in his possession. The more generally these data are used, the more nearly will the table represent average conditions. With these average conditions and their probable limits of error known, the application of resistors from the classification table will be made relatively simple and both manufacturer and user will be benefited. Any engineer having difficulty with resistors on a particular application and finding that he has selected the

correct classification may then examine this particular application with a view to determining in what way it differs from the normal. P. B. Har-

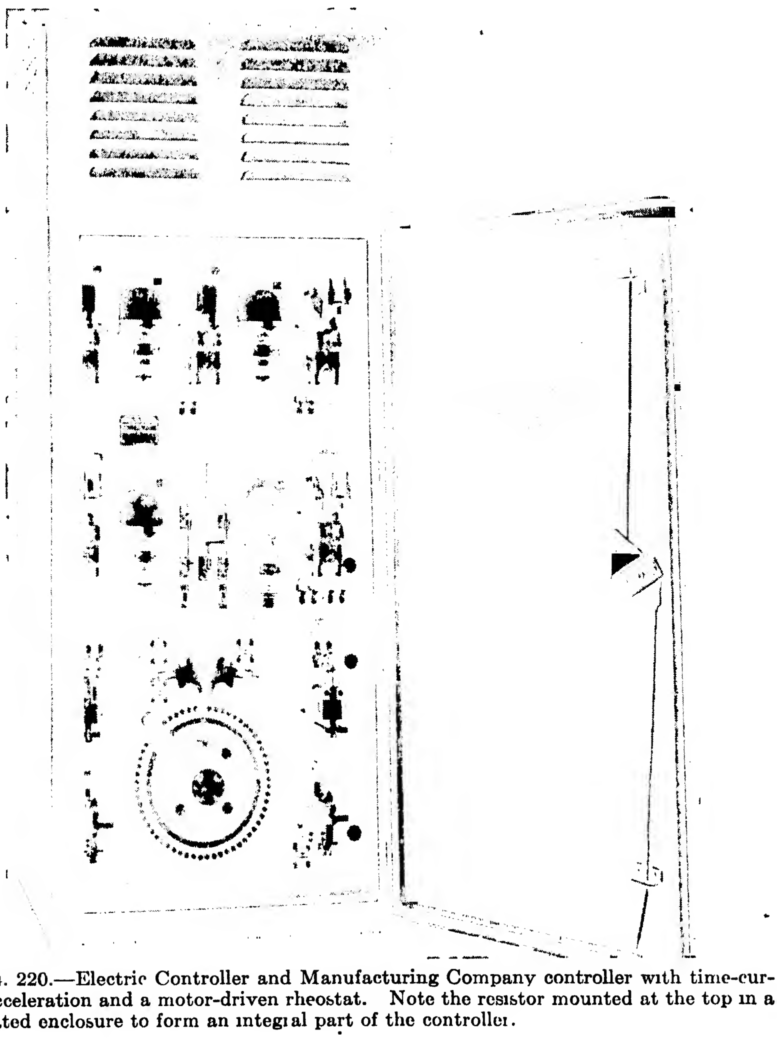


FIG. 220.—Electric Controller and Manufacturing Company controller with time-current acceleration and a motor-driven rheostat. Note the resistor mounted at the top in a ventilated enclosure to form an integral part of the controller.

wood in his book, "Control of Electric Motors," gives additional information for resistor design.

CHAPTER XV

MANUAL CONTROLLERS

This chapter will deal particularly with manual controllers of the reversing type, which may be used for regulating the speed of the motor as well as starting, stopping, and reversing. A manual controller is one that has all its basic functions performed by hand. It is the opposite of a power-operated controller. The manual controller may be complete in itself or may form only part of the control equipment, as a master switch. The term "controller" is a broad designation. A controller used for accelerating a motor to normal speed in one direction is usually called a "starter." Types of faceplate starters are shown in Chap. II.

TYPES OF MANUAL CONTROLLERS

The Drum Controller.—The drum controller is the best known and, at present, the most commonly used form of manual controller. When it is used only for reversing a motor, it is known as a drum reverse switch, but generally it has additional points for acceleration and speed control. Types of drum controllers are shown in Fig. 221. The controller consists of a series of stationary fingers that engage segments on the surface of a cylinder or drum. The cylinder is revolved by a handle and is enclosed in an iron case with a sheet-iron cover. The fingers may be mounted in a single row on one side of the drum or in a double row, on opposite sides of the drum.

The drum cylinder usually consists of one or more castings clamped to an insulated square or hexagonal steel shaft; copper straps are attached to the outer surface for engaging the contact fingers and are sometimes provided with removable arcing tips. In some controllers the drum castings are made of brass or copper and engage the fingers directly without the use of removable contacts, but in most cases the drum is provided with removable contact segments.

The drum shaft has a notched wheel attached either above or below the drum. This is called a "star wheel," the notches corresponding to each of the operating positions of the controller handle. Whenever a set of contacts is in its proper position on the drum, a roller is forced into one of the notches on the star wheel by means of a spring. This indicates the exact operating position of the handle for each notch.

The most important item in the design of a drum controller is the contact finger, of which many different types have been made. Each

FIG 221.—General Electric drum controllers

manufacturer has a particular design which he features and which has its advantages and limitations. Figure 222 shows one type of finger that contains all the elements usually found in the various designs. There is a contact-carrying part that engages with the surface of the drum and is flexibly mounted on a finger base. The pressure between the drum and the finger is maintained by a spring, and the current passes from the finger to the terminal through a flexible shunt. The finger base is securely clamped to an insulated iron base and is sometimes provided with an arc shield between it and the drum.

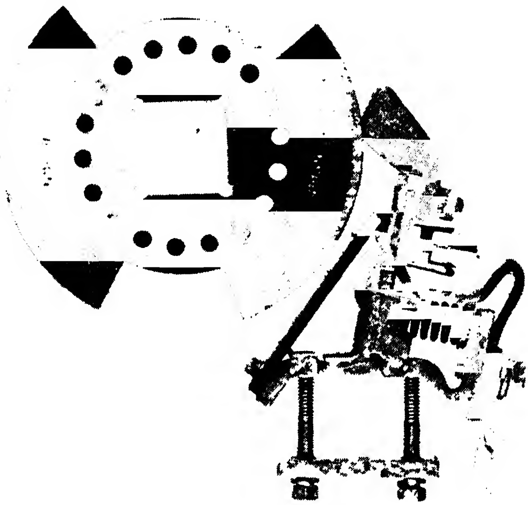


FIG. 222.—Westinghouse drum controller segment and contact finger.

When the controller is in the Off position, the fingers are not in contact with the surface of the drum, being opposite the cutaway portion of the drum. When the drum is rotated toward the finger base, the copper straps on the surface of the drum engage the contact fingers, lifting them and causing them to ride over the copper surfaces. The ends of the fingers are bent outward so as to strike the straps on the drum obliquely and are thus lifted without being stubbed. When the finger and the drum are in contact and the drum is rotated away from the finger base, the finger, being in tension, is under little strain; but when it is first engaged by the drum, it is in compression and must be of sufficiently rigid construction to withstand the strain then exerted upon it. When they are in contact, the fingers are lifted through a distance of $\frac{1}{16}$ in., a stop on the finger permitting it to be adjusted to obtain this condition. Sliding

on the drum wears the finger away, so that it must be adjusted from time to time to maintain the proper contact pressure.

When returning the drum to the Off position, the contact segment in moving away from the finger forms an arc. This arc is established on one side of the contact surface of the finger and at the edge of the drum segment, so that the burning does not take place on the parts ordinarily carrying current. A magnetic blowout is usually supplied with direct current controllers to extinguish this arc. The blowout may consist of a single coil and a common magnetic circuit for all of the different fingers, or an individual blowout may be attached to each finger. The latter arrangement gives better results, but its extra expense may not be justified except for heavy duty.

FIG. 223.—Westinghouse cam controller.

The current that a contact finger will carry depends upon the width of the finger and the pressure between it and the surface of the drum. Tests indicate that if this pressure is in excess of 10 lb. per in. of width some form of lubricant should be used or the cutting becomes excessive. The best form of lubricant is a good grade of vaseline spread thinly over the drum segments. Most controllers are designed for contact pressures less than that given above, so that the lubricant is not necessary, although if the drum is kept clean and lubricated the contact fingers will last longer.

The armature resistor is almost always mounted separate from the drum controller. Where the controller provides for both armature and field control, the resistor for the field rheostat may be mounted as part of the controller. The ordinary reversing controller can be assumed to have a separate armature resistor.

The Cam Controller.—Cam controllers have the same general appearance as the drum controllers and are mounted and operated in the same manner, but the contact element is different. In place of the rotating cylinder is a shaft carrying a set of cams, which engage and close a series of contactors that replace the drum fingers (see Fig. 223).

The contact mechanism is illustrated in detail in Figs. 224–226. It consists of a stationary element, which may or may not be provided with a blowout, and a movable element held open by a spring and closed by a cam. The action of this contact is exactly the same as that of the magnetic contactor and the same contacts are used.

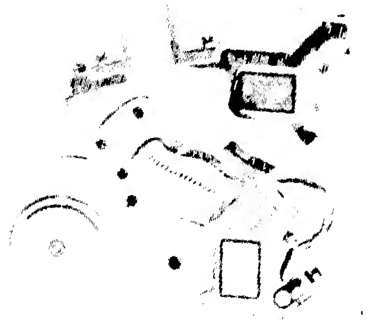


FIG. 224.

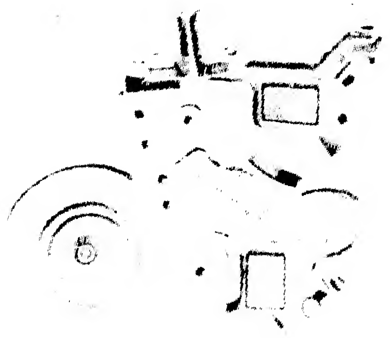


FIG. 225.

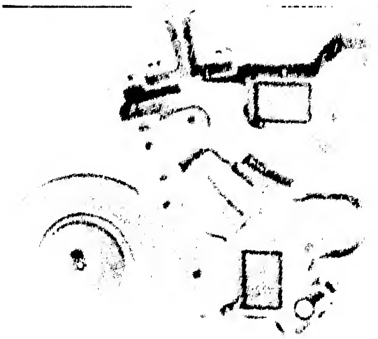


FIG. 226.

FIGS. 224–226.—Details of contactors used in cam controllers. The contactors may also be clamped to insulated plates instead of bars. These contacts are of the rolling type —note the action during closing. The contact is established at the tips and rapidly transferred to the heel or lower portion of the contacts during the closing process. This process takes place by a rolling action. When opening the process is reversed, throwing all of the arcing to the tip of the contact.

The illustration shows the three positions of the contact: (1) when open; (2) when just touching at the tip, and (3) when it is entirely closed, making contact at the heel. In opening it the process is reversed. This rolling action from the tip to the heel and back again in opening causes the arc to be broken at the tip and the current to be carried at the heel. By the use of rolling action instead of a sliding action in closing, the mechanical wear is eliminated and much heavier pressures can be used. A more complete discussion of this contact is given in Chap. IV.

The current is carried from the movable contact to the terminal by means of a flexible shunt; one end of the spring is insulated so that no current can pass through this member. On account of the spring's being located a considerable distance away from the contact, it is not directly affected by the temperature of the contact or the arcing and is, therefore, in no danger of having its temper drawn, owing to excessive loads.

The movable contact is attached to a block, which in turn is fastened to the hinge member. The surface between this block and the hinge

a b

FIG. 227.—Cutler-Hammer drum-type master switch: a, with cover in place; b, with cover removed.

member is corrugated and one of the holes is slotted so that this block can be adjusted to give the proper contact action. After this adjustment is made, it should not be necessary to change this block when renewing contacts, as all the contact wear takes place at the tip and does not affect the location of the current-carrying parts.

Various combinations of switches can be obtained by changing the number of contactors and the shape of the cams. The length of the frame can be adapted to the desired combination by changing the length of the insulating bars and the sheet-iron cover.

Both the drum type and the cam type of controllers can be provided with either a rotating handle or a lever handle. They may also be mounted vertically on the rear of the panel and operated by a handwheel on the front of the panel through suitable gearing. If the controller is mounted back of the panel with the shaft horizontal, the shaft can be extended directly through the panel without the use of gearing.

Both types of controllers have been built motor operated. In that case, the construction is the same as for manual operation, the handle being replaced by a reduction gear and a pilot motor.

The drum controller is more compact for certain switching combinations, such as reversing. The cam type is easily designed for complicated

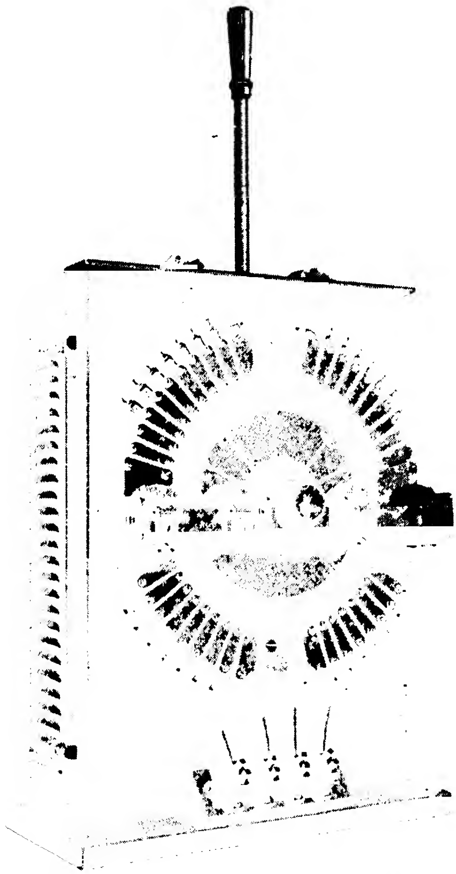


FIG. 228.—Electric Controller and Manufacturing Company face-plate controller—known to the trade as the "Dinkey controller."

switching, and new combinations can be more easily made, as these combinations are accomplished by cutting cams of different shapes. The cam units can be removed individually without dismantling the controller. The same is true of the contact fingers of the drum controllers; however, the drum shaft must be taken out to replace drum segments, after which it is advisable to true the segments in a lathe before reassembling them in the controller. The cam controller has a blowout that compares favorably with that of the magnetic contactor and that is always in the proper

direction. Both types when enclosed have a restricted arcing space and are, therefore, more limited as to severity of service than are magnetic contactor controllers.

The Faceplate Controller.—One of the most popular forms of manual controllers in steel-mill service is known as the Dinkey controller (Fig. 228). It somewhat resembles the ordinary faceplate rheostat, although it is much more rugged in construction. A series of stationary contacts are mounted on an insulated base, and a pair of brushes making contact with these rotate around a central shaft. The brushes make contact between an outer and an inner row of contacts. The handle usually projects from the top of the controller and actuates the brush arms by means of a pinion and gear segment, so that a relatively small motion of the handle is multiplied into a large motion of the brushes. The stationary contacts are made removable from the face of the controller without disturbing the electrical connection. The brushes can also be renewed when necessary. The resistor is mounted in the controller frame back of the faceplate, the whole forming a self-contained unit.

A modification of this type of controller, known as the "grindstone" type, is now obsolete. The contacts of this controller are mounted around the periphery of an insulated base, in the semblance of a grindstone, to which fact it owes its name.

The Compression Type of Controller.—Controllers of the compression type (Fig. 217) differ from all other types of controllers. Instead of a number of contact segments connected to taps on the resistor, several columns of graphite disks are used, the change in resistance being obtained by varying the pressure between the disks. This form of resistor is shown in greater detail in Figs. 216-218.

The illustration shows the manual type of controller, but other forms of this controller are made, using contactors.

COMPARISON OF TYPES

The two controllers described last, above, have the resistor self-contained with the switching mechanism, whereas the first two usually have separately mounted resistors. The drum and cam types may have either a rotating or a lever handle, but the other two types are always provided with lever handles. The four are representative of many that are now being successfully used. Other forms of controllers are built and doubtless from time to time improvements will arise, but in the present state of the art the types described show the principles used in all manual controllers.

Manual Controllers versus Magnetic-contactor Controllers.—The advantages and limitations of manual controllers depend to a large degree upon their sizes and application requirements. The following list of

advantages and limitations should be interpreted broadly, as there are many applications for manual controllers that would not justify the use of contactor control.

Advantages.—The advantages of a manual controller, as compared with a magnetic-contactor controller, are these:

1. The first cost is less.
2. The space occupied by the controller is usually less and the weight is less. In some applications the weight and space requirements are often a determining factor.
3. They are more simple. Manual controllers usually have no electric interlocks, so that the wiring connections can be easily followed.
4. These controllers are readily enclosed to protect them against dust, dirt, and moisture. The drum and cam controllers are often made watertight for use on shipboard.

Limitations.—The limitations are as follows:

1. The larger sizes of manual controllers require more effort to operate and may, therefore, tire the operator if frequent use is necessary.
2. The contacts will wear more rapidly, as their operation is not so positive. The quicker the contacts are opened and closed, the less is the maintenance cost.
3. The arcing takes place near the operator. This is not objectionable in small controllers, but it is safer to have the main arc-rupturing parts located remote from the operator, where a considerable amount of power is being handled.
4. The larger sizes of manual controllers occupy more space than the master switch of the magnetic type and on cranes and some other applications, therefore, a large manual controller may interfere with the operator's seeing his work.
5. A separate protective panel is required for manual controllers, to obtain overload and low-voltage protection, required in many applications. In some watertight controllers it has been found necessary to mount the protective panel in the same case as the master controller.

VENTILATING REQUIREMENTS

In rupturing the arc, ionized gases are produced, which must be removed by ventilation. Where the manual controller is enclosed, the air space surrounding the arc-rupturing parts is limited and the ventilation is poor. Where the circuit is opened and closed frequently, trouble may result from the accumulation of these gases. This difficulty does not arise with small controllers and may be avoided in the larger type by ventilating the enclosing cover. (These limitations may occur also in the magnetic type of controller where the enclosure is restricted.) This condition is sometimes overlooked so that a properly designed controller has been discredited, whereas improper application was the cause.

Whatever type or design of controller is used, provision must be made for disposing of these ionized gases. The more quickly the arc is ruptured, the less gas will be produced. When an enclosed controller is used, the arcing heats up the air space within the enclosure and limits

the current-carrying capacity of the contacts and other parts. The more frequent the arcing, the greater the heating. This is a limitation sometimes overlooked.

Manual controllers are usually rated either for intermittent duty or for continuous duty. Continuous service presupposes only a small amount of arc rupturing. Intermittent service must assume a certain amount of heat to be generated by the arc. The more frequently the circuit is opened, the less time the current-carrying parts will be in circuit, and the increase in air temperature inside the enclosure due to arcing, therefore, will be counterbalanced by a smaller amount of energy lost in heating the current-carrying parts. Conditions may arise, however, under which the current is left on longer than was intended, or the current is ruptured more frequently than was estimated when the controller was rated. Engineering skill, therefore, is required in selecting a controller, to determine whether any unusual conditions of this kind exist in a particular application.

CHAPTER XVI

DIRECT-CURRENT MAGNETIC-CONTACTOR CONTROLLERS

TYPES OF MAGNETIC-CONTACTOR CONTROLLERS

Magnetic-contactor controllers may be divided broadly into nonreversing and reversing controllers. Where several contactors are used for short-circuiting sections of the resistor in the armature circuit, the connections to the operating coils of these contactors can be made in succession by means of a drum-type master switch. In this case, the motor can be operated with more or less armature resistance, depending upon the number of contactors whose circuits are closed through the master switch. The number of resistance steps can be altered to suit the application. The writer believes that one step of resistance is sufficient for starting d.c. motors up to 15 hp. 230 volts, where the starting duty is light, and that two steps may be used for heavy starting. If it is desirable to regulate the speed of the motor, additional steps should be provided. The acceleration of the motor quite frequently is automatic, even when several running points are provided.

Nonreversing Controllers.—Nonreversing controllers are usually connected on one side of the motor circuit only and consist of a line contactor, a resistor, and one or more contactors for short-circuiting the resistor. A two-pole knife switch or circuit breaker, mounted separate from the control panel, is usually required with this type of controller, the knife switch being connected so that it will disconnect both sides of the motor and the controller from the line. The line contactor may be provided with a bottom contact for short-circuiting the armature of the motor through a fixed resistance, to give dynamic braking when the line switch is opened. A diagram of a controller arranged for dynamic braking is shown in Fig. 230.

In some cases it is desirable to open both sides of the motor circuit when the controller is in the Off position. This can be done by providing two line contactors. This arrangement, however, is not usually employed, as it adds to the expense and opening the knife switch by hand accomplishes the same result. The knife switch is needed so that the contactors can be disconnected from the line to renew the contacts or to make adjustments.

Reversing Controllers.—In order to reverse the armature of a d.c. motor it is necessary to disconnect both sides of the armature from the

line. This necessitates the use of four single-pole contactors or two double-pole contactors, two contacts being closed for either direction of operation. It is the usual practice to arrange either a mechanical or an electrical interlock between these contactors, so that the forward and the reverse contactors cannot both be closed at the same time, as this would result in a short circuit and might injure the apparatus. The resistor in

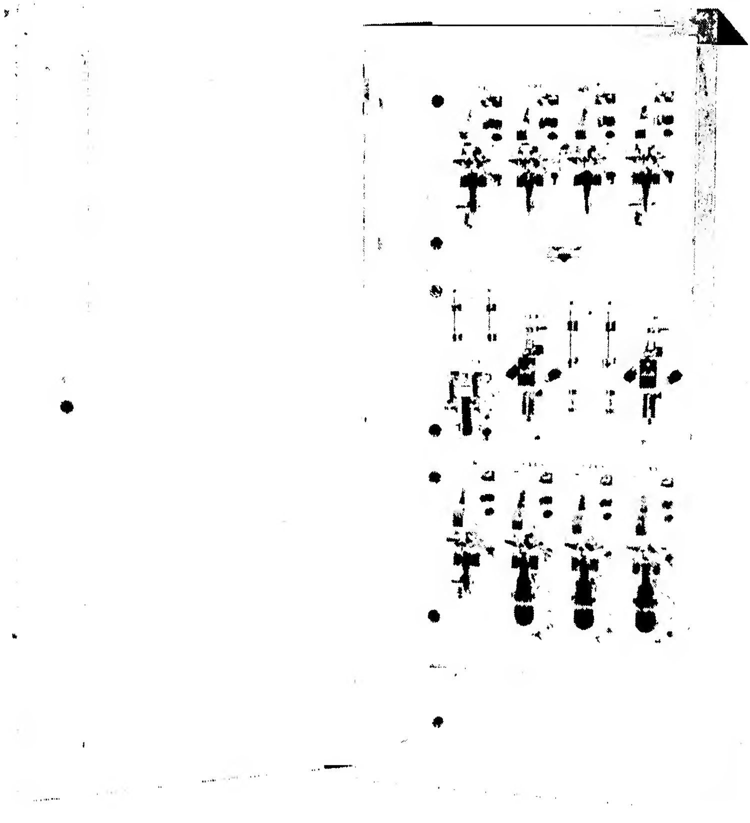
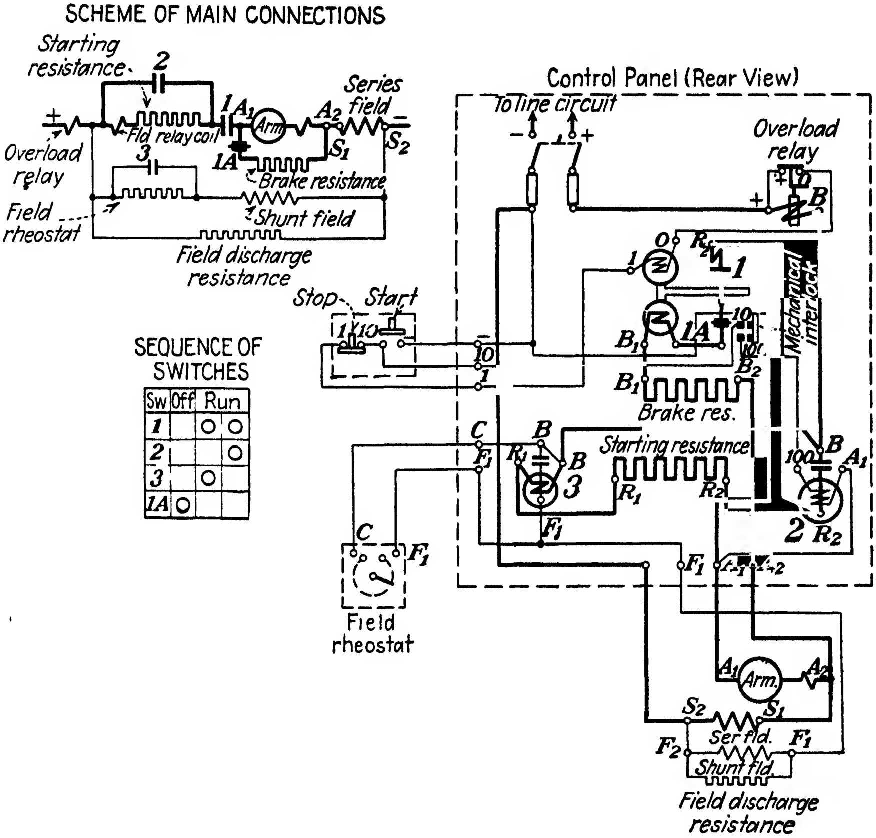


FIG 229.—Cutler-Hammer magnetic-contactor controller for reversing and plugging service.

series with the armature is short-circuited in steps by magnetic contactors in the same manner as for nonreversing controllers. Frequently the resistor is connected directly to one side of the motor, so that the line contactors in their Off position disconnect the armature entirely from the line, as is shown in Fig. 231. Since both sides of the motor circuit are opened by contactors, the shunt field cannot be connected so that it will discharge through the armature of the motor. It is, therefore, good

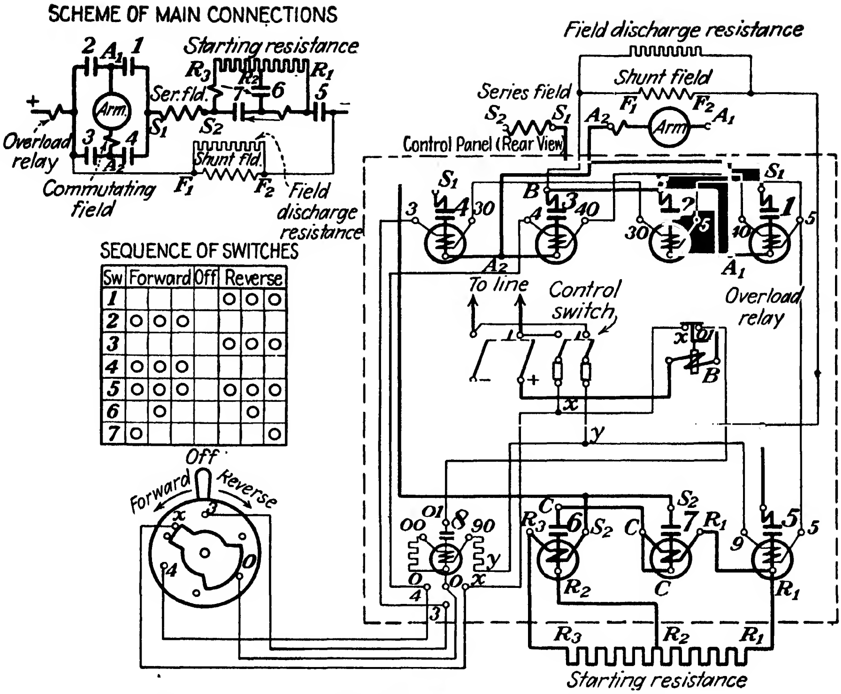
practice to provide the shunt field with a parallel resistance to take up the inductive discharge when the field circuit is opened. If this resistance is omitted, a high voltage is generated in the field windings, which may ultimately result in puncturing the insulation.



Sw	Off	Run	
1		O	O
2			O
3		O	
1A	O		

FIG. 230.—A nonreversing d.c. magnetic-contactor controller. Pushing the Start button results in closing line switch 1, which closes the mechanical interlock contacts and opens the bottom contacts at 1*A*. The motor then starts, with the starting resistance in series. Switch 3 simultaneously short-circuits the field rheostat, ensuring full field as long as the starting resistance is in series with the armature. When the counter e.m.f. of the accelerating armature reaches a predetermined value, switch 2 closes and shunts the starting resistance out of the circuit. Short-circuiting this starting resistance causes switch 3 to open, so that field control is possible by the use of the field rheostat, after the motor comes up to speed. The dynamic braking resistance is connected across the armature terminals whenever switch 1 is open. Series operating coils on 1*A* prevent the motor from being started while the heavy dynamic braking circuit is flowing, and also ensure good contact pressure.

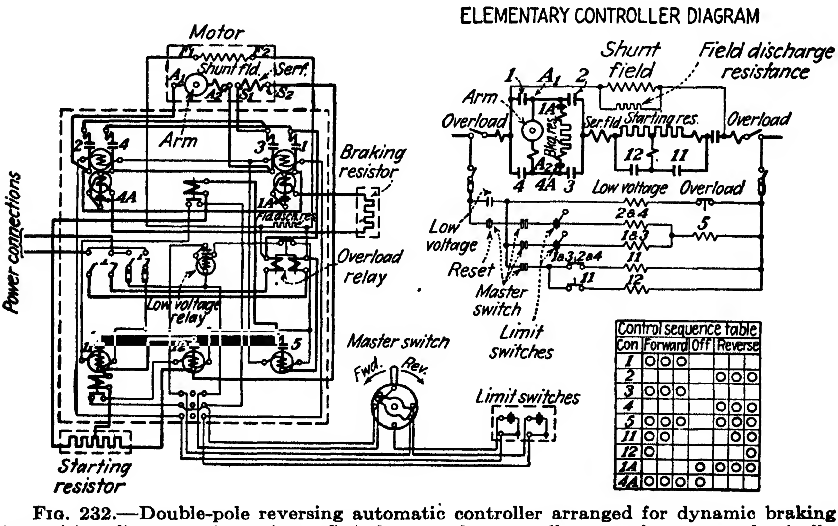
The reversing controller can be arranged for dynamic braking by providing a bottom contact on one of the forward and one of the reverse direction switches, so connected that when both of these switches are



Sw	Forward			Off	Reverse		
1					O	O	O
2	O	O	O				
3					O	O	O
4	O	O	O				
5	O	O	O		O	O	O
6		O				O	
7	O						O

FIG. 231.—A d.c. reversing magnetic-contactor controller.

The master switch makes contact between 0 and x in the Off position between 0 and 4 in the Forward position; and between 0 and 3 in the Reverse position. Switch 8 provides overload and low-voltage protection. Its operating coil is connected directly across xy through the master controller in the Off position, and (by an interlock underneath coil 8 connecting 0 and x) across xy through the overload relay in the running positions. This means that in case the motor is stopped for any reason, it is impossible for it to be restarted until the master controller has been turned to the Off position. Switches 6 and 7 are of the magnetic lock-out type, and cannot close until after the current flowing on their control coils drops below a predetermined value.



Con	Forward			Off	Reverse		
1	O	O	O				
2					O	O	O
3	O	O	O				
4					O	O	O
5	O	O	O		O	O	O
11	O	O				O	O
12	O						O
1A				O	O	O	O
4A	O	O	O	O			

FIG. 232.—Double-pole reversing automatic controller arranged for dynamic braking from either direction of rotation. Switches 1 and 3, as well as 2 and 4, are mechanically connected and controlled by the same operating coil, thus forming a double-pole contactor. Dynamic braking is accomplished, as in Fig. 230, by bottom contacts 1A and 2A.

open the armature will be short-circuited through a resistor, as shown in Fig. 232.

FIELD RHEOSTATS

Where a controller is used with an adjustable-speed motor, a field rheostat is used for changing the resistance of the field circuit to adjust

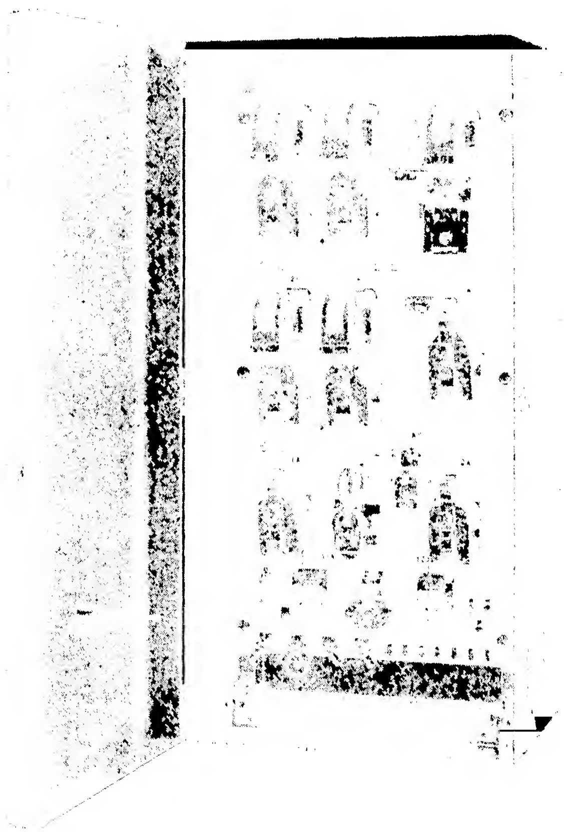
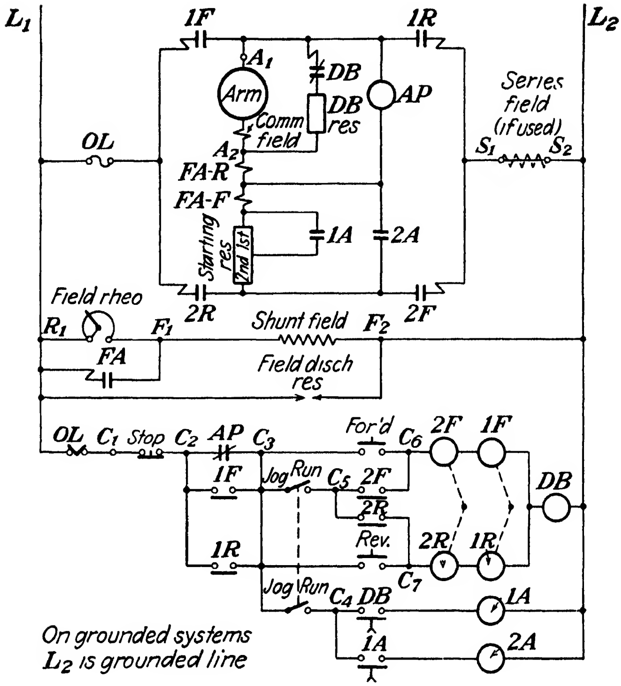


FIG. 233.—Square D type VG-2 starter for an adjustable speed motor. This starter has resistor-shorting contactors closed in sequence at predetermined intervals after the line contactor closes. The timing period for each contactor is controlled by a pneumatic time-delay unit (see Fig. 72).

the speed of the motor. This field rheostat may be mounted on the controller panel or separate from it. It is considered better practice to mount this rheostat separate from the control panel, so that the operator will not be required to place his hand close to the magnetic contactors when they are in operation. The separately mounted field rheostat can be covered, to prevent the operator from coming in contact with any live



Line diagram for D.C time limit acceleration reversing starter with three points of acceleration

FIG. 234.—Diagram for controller in Fig. 233.

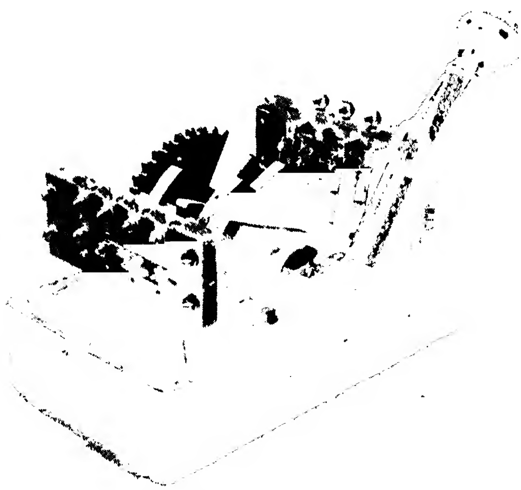


FIG. 235 —Westinghouse cam-type master switch with lever handle and cover removed.

parts. Usually the contactor panel is quite large and must be mounted in a more or less inaccessible place. The field rheostat, however, is small and can be located close to the master switch. Sometimes the master switch and the field rheostat are combined in one unit.

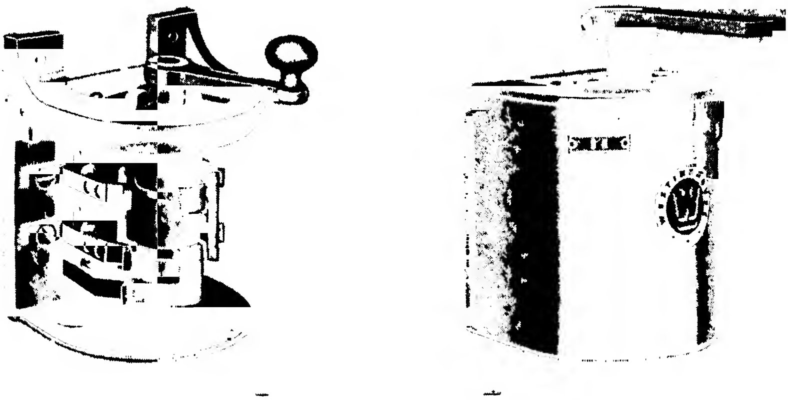


FIG 236 —Westinghouse drum-type master switch

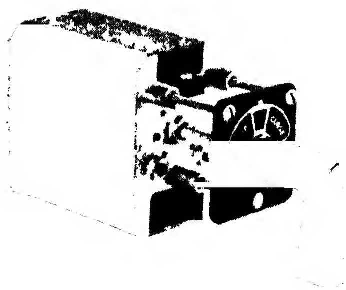


FIG 237.—General Electric master switch for switchboard mounting.

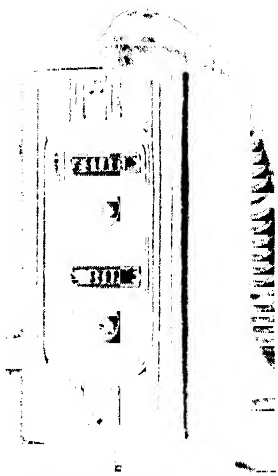


FIG. 238.—Westinghouse push-button station

CONTROLLER SUMMARY

To sum up: A controller is made up of a magnetic contactor panel, either reversing or nonreversing, with or without dynamic brake. Some form of master switch is provided to operate the controller, and a field

rheostat may be added. This gives the essential elements for the control of an electric motor.

MASTER SWITCHES

The master switch is an auxiliary switch that serves to govern the operation of contactors and auxiliary devices of electric controllers. It

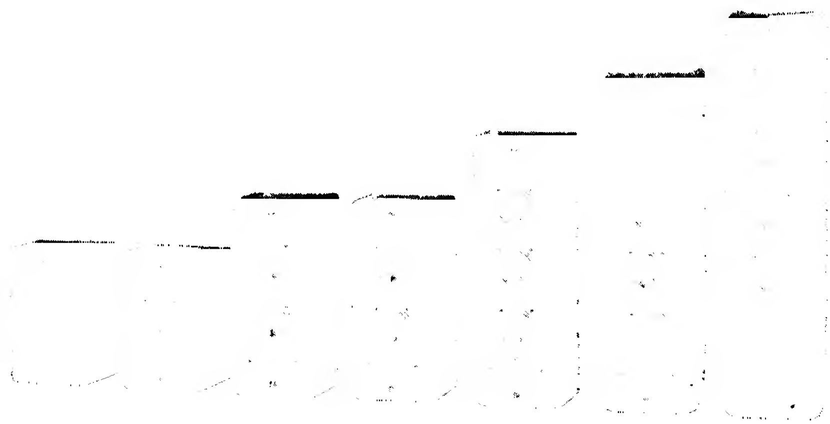


Fig. 239—General Electric push-button stations

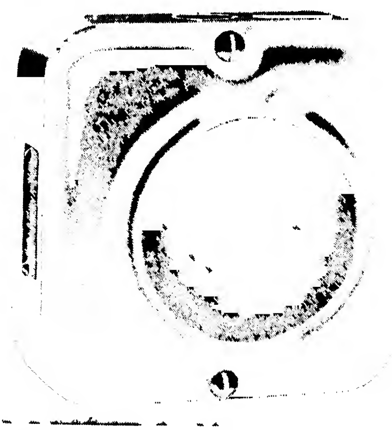


Fig. 240—General Electric heavy-duty push-button station.

usually takes the form of push button, float switch, pressure switch, thermostat, or drum switch. Other forms, of course, are in use, and any device that opens and closes the circuit may be used as a master switch.

The push-button switch is the most common and is perhaps used more than all the other types combined. An ordinary start-and-stop push

button is shown in Figs. 238 and 239. More elaborate combinations of push buttons are used for printing presses, electric elevators, and other applications where a complicated sequence of operation is required.

A float switch is shown in Figs. 112–113 and a pressure switch in Fig. 111. These switches are used in connection with pumps and similar installations. The float switch, as its name implies, consists of a hollow metal box used as a float, which opens and closes the master switch for

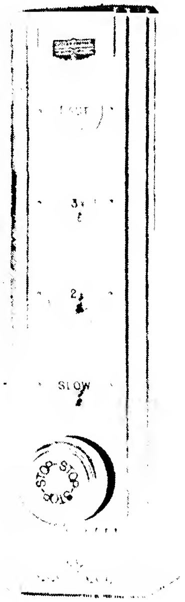


FIG 241 Cutler-Hammer push-button station with a special Stop push button

FIG 242.—Square D Company waterproof push-button station

different levels of the liquid in which it is placed. The pressure switch has a diaphragm, which opens the contacts at the maximum pressure and closes them at the minimum pressure for which it is adjusted. Various forms of thermostats are used in connection with refrigerating machinery for starting and stopping the motor-driven machinery at different temperatures.

A master switch of the drum type is shown in Fig. 236. This is usually in the form of a small drum controller and may be operated by the rotation of a handle or with a forward-and-back motion of a lever (Fig 227). Under this class should be included also switches in which the contacts are arranged on a faceplate instead of a drum, and where the contacts are operated by cams. The drum type of master switch is usually

applied where the sequence of operation is more or less complicated; also, where frequent operation is required.

Methods of Operation.—Most master switches may be connected to either reversing or nonreversing controllers. Two general methods are employed, one of which is known as "low-voltage release" and the other as "low-voltage protection." They are defined as follows:

Low-voltage Release.—The effect of a device operative on the reduction or failure of voltage, to cause the interruption of power to the main circuit, but not preventing the re-establishment of the main circuit on return of voltage.

Low-voltage Protection.—The effect of a device operative on the reduction or failure of voltage to cause and maintain the interruption of power to the main circuit.

The reason for making the above distinction is largely a matter of safety. If the motor drives a woodworking machine, for instance, the machine may be at rest, owing to the absence of line voltage. Under these circumstances, the operator might be engaged in adjusting the machinery, or for some other reason might have his hands close to the cutting tools. If the line voltage is restored at such a time, the operator may easily be injured. This applies to a variety of machinery. Gears are a source of danger from this cause. These gears are usually protected under operating conditions, but this protection might be removed when the machine is at rest. In order to guard against accident from this cause, the master switch is so connected to the controller as to afford low-voltage protection. This requires the operator to perform a manual operation on the master switch in order to start the motor after it has once come to rest because of a failure of voltage.

Where the motor operates a fan or a pump, it is very desirable to have the apparatus start automatically after a failure of voltage. In such cases there is little or no danger resulting from the automatic starting of the motor, and a great deal of inconvenience and possible danger might result from the failure of the motor to start when the voltage is restored to the line. The master switch under such conditions is connected to give low-voltage release. This arrangement automatically starts the motor again, when the line voltage is restored.

OVERLOAD PROTECTION

It is usually necessary to provide some form of overload protection in connection with the controller. The least expensive form of protection is the fuse, usually of the cartridge type. These fuses have a certain amount of time element and therefore can be used for control apparatus. When a motor is started or during its operation, heavy currents may be taken by the motor for a few seconds. These do not injure the motor or

the controller, and therefore it is desirable to have a time element in the overload device. This occurs to a limited extent when a special type of enclosed fuse is used.

Another common form of overload protection is a series relay that opens a contact by means of a magnet when the current exceeds a certain value. These relays should have a dashpot to obtain a time element, so that the relay can be given a setting more nearly equal to the full-load current of the motor. Thermal overload relays are now more generally used for motor protection. See Chap. XX for a description of different types. Where a magnetic contactor is used on only one side of the line, a single-pole relay may be used with this contactor, but it is necessary to use a fuse on the other side of the line. The advantage of a relay is that it can be restored to its normal position very easily. The fuse, however, must be replaced by a new one. If a combined relay and fuse is used, it is usual to select a fuse with a higher rating than the setting of the relay, so that under ordinary conditions of overload the relay will operate and save the fuse.

It takes some time to raise the temperature of a motor to a dangerous point when it is overloaded. If this overload is within the commutating limits of a motor, the additional load will not injure the motor until the temperature has been raised to the danger point. This usually takes from 5 min. up to a half hour or more, depending upon the size of the motor and the amount of overload. If the overload is continued indefinitely, it will injure the motor, but short periods of operation are permissible. The result has been that operators set the overload protection high enough so as not to operate on short-time peak loads. Therefore, the motor is without any real protection against continuous overloads. Very few fuses, overload relays, circuit breakers, or similar apparatus give complete protection to industrial motors. They operate in case of short circuits or abnormal overloads, but usually they are set too high to open on a small overload, which may be sufficient to injure the motor if continued for a long time. There are time-element overload devices that have time elements of 5 to 30 min., instead of 5 to 30 sec., as in the case with most of this apparatus. The longer the time element can be made, the more desirable it is for the operation of motors.

It is often stated that an overload relay having a long-time element will not operate quickly enough in case of a short circuit or a ground to protect the motor. Standard practice, however, requires the use of fuses or a circuit breaker at the point where the motor circuit leaves the main power wires. The fuses or the circuit breaker at this point must be set to protect the wires leading to the motor. If these wires are made a little larger than for the full-load capacity of the motor, the circuit breaker at this branch point may be set so that it will not operate on normal over-

loads of the motor, but will protect the motor under abnormal conditions, and also afford protection to the wires leading to the controller. The ideal protection, therefore, is feeder protection against short circuit and a time-element overload device on the controller that will protect the motor against continuous overloads, while permitting overloads for short periods of time.

Overload relays are commonly made up in three forms:

1. The first allows the armature to return to the open position immediately after the overload has been removed. The function of such a relay is to open the line contactor. Connections are made so that the contactor will be retained in the open position until the master switch is manipulated.

2. The overload relay is provided with a catch, which holds the armature in the closed position and requires the energizing of a separate magnet to release the catch and restore the relay to its normal condition.

3. This is the same as 2, except that the catch is released by hand instead of by a magnet. This is objectionable because the operator must place his hand on the device, which is in the neighborhood of live parts.

Arrangement 1 is the most common and is usually preferred, owing to its simplicity and cheapness. Arrangement 2 is usually connected to the master switch, so that the relay is reset by moving the master switch to the center or off position.

APPLICATIONS

The magnetic-contactor controllers described above are those having the most general application. A few of the typical applications are for motors driving line shafting, pumps, machine tools, woodworking machinery; in fact, any apparatus that is motor driven that does not require a special arrangement of circuits.

CHAPTER XVII

ALTERNATING-CURRENT CONTROLLERS

Many types of d.c. motors have been built and a variety of methods of control have been devised. However, very few a.c. motors, other than induction motors, are used in industrial work, and the methods of control in common use are quite simple.

WOUND-SECONDARY MOTORS

When resistors are used for accelerating or controlling the speed of induction motors, they are usually placed in series with the three-phase wound secondary of the motor. The ends of this winding are brought out to three slip rings on the motor shaft, so that resistance may be inserted between each of the three rings. The method of control corresponds very closely to that of a compound-wound motor with only a small amount of series field. In studying this type of control and applying it, the problem is simplified if the operating conditions are considered to be those of the corresponding d.c. motor and no attempt is made to analyze the complicated reactions that are taking place in the wound-secondary motor.

This method of control requires the use of a primary switch, which should be separated electrically from the part of the control that is used for changing the resistance of the secondary circuit. Usually the secondary is wound for less than 600 volts, and in standard motors the secondary voltage and current do not change materially for different primary voltages. This fact makes possible the use of the same secondary controller with a number of different primary switches. For a primary potential of 600 volts or less, air-break switches are used. If it is 2,200 volts or more, oil switches are frequently employed, although for certain classes of service air-break magnetic contactors have come into use.

Where the motor operates in one direction only, the primary switch often consists of a circuit breaker, and either a faceplate or drum-type secondary controller is used. If automatic acceleration is required, both primary and secondary control consist of magnetic contactors, as shown in Figs. 243 and 244.

If the motor is to be reversed at frequent intervals, a drum controller having both primary and secondary switches is generally used for small motors. Large motors usually require magnetic contactors, in which case

the same master switches and the same method of overhead protection may be employed as for d.c. control. Low-voltage release or low-voltage protection can be obtained in the same way.

There are several methods for arranging the resistors in the secondary circuit of wound-rotor motors. In each case, sections of resistance are

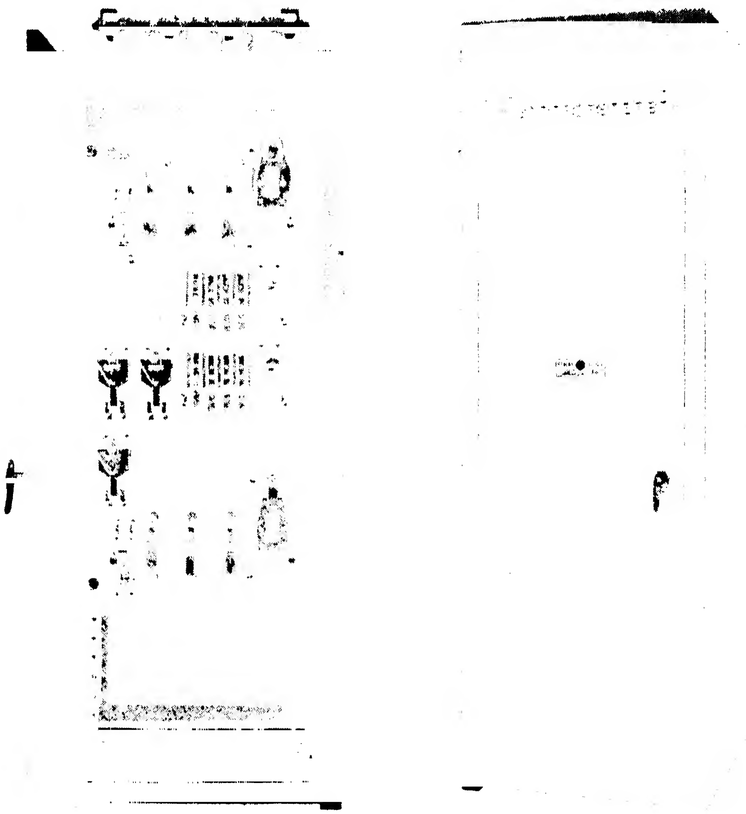


FIG 243 —General Electric controller for wound-secondary induction motors 4-point 150 amp

short-circuited by contactors One method consists of short-circuiting these sections simultaneously on all three legs of the circuit This keeps the resistance balanced and is theoretically the best method to employ. It requires the use of two contactors or their equivalent for each step of control.

A more economical method consists in short-circuiting the resistor in one leg of the circuit at a time. This requires the use of only one contactor per step and uses the control equipment to much better advantage

Theoretically the unbalancing that results from this method of control is objectionable. A careful analysis of this problem shows that when the

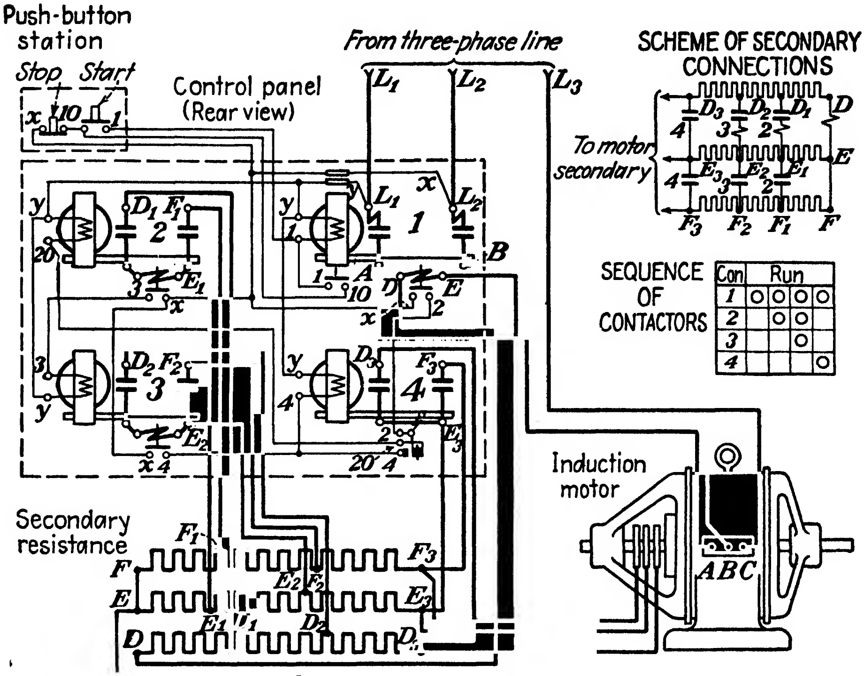


FIG. 244.—Automatic controller for a three-phase induction motor. Contacts 1-10 are held open mechanically when switch 1 is open and closed when switch 1 is closed. Contacts x-2 are held open by a spring when switch 1 is open, and the spring pressure is released when switch 1 closes. These contacts are still held open magnetically, however, until the current in the coil DE drops below a predetermined value. Contacts x-3 and x-4 are similarly interlocked to switches 2 and 3, respectively. The interlock at the bottom of switch 4 is thrown to the right when the switch is open and to the left when the switch is closed.

Pushing the start button causes line switch I to close, and this switch is held closed through contacts 1-10 after the start button is released. Switch 2 is closed through circuit x-2-20-y as soon as the current in coil DE drops below a predetermined value. Switches 3 and 4 are similarly closed automatically when the current in D_1E_1 and D_2E_2 drops below the predetermined value. The interlock below switch 4 interrupts the control circuits to switches 2 and 3, allowing them to drop open, and holds switch 4 closed independently of the interlocks of switches 2 and 3. Pushing the stop button interrupts the control circuit of switch 1, causing it to open; and this action opens contacts x-2, allowing switch 4 to open.

unbalancing is properly arranged the performance of the motor is not materially changed from balanced operation, and a number of other advantages are secured.[1]

[1] An analysis of the problem of unbalanced secondary operation is discussed in detail in a paper by A. A. Gazda, presented before the A.I.E.E. in February, 1917. His theoretical analysis was carefully checked by test, so that the results given represent actual operating conditions.

In the discussion of this question the inductance and resistance of the secondary winding of the motor will be neglected for the sake of simplicity, as their effect is very small on the total results. Figure 246 shows a

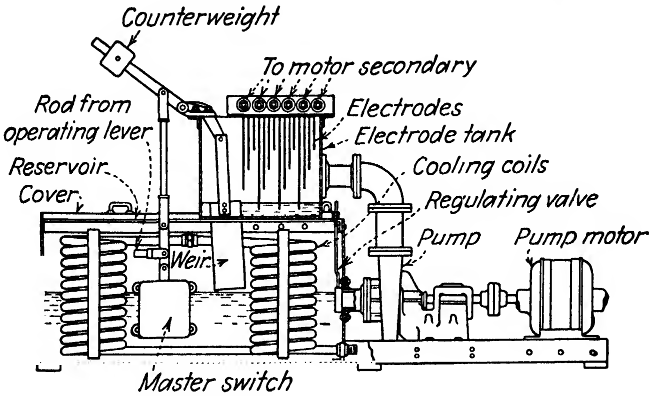
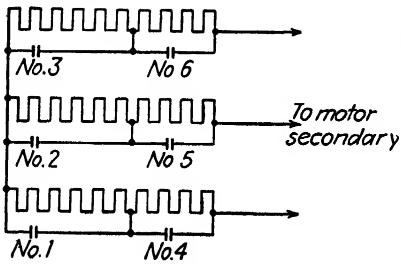


FIG. 245.—Liquid controller for large wound-secondary induction motors.



Sw	Run						
1		O	O	O	O	O	O
2			O	O	O	O	O
3				O	O	O	O
4					O	O	O
5						O	O
6							O

FIG. 246.—Sequence of switches.

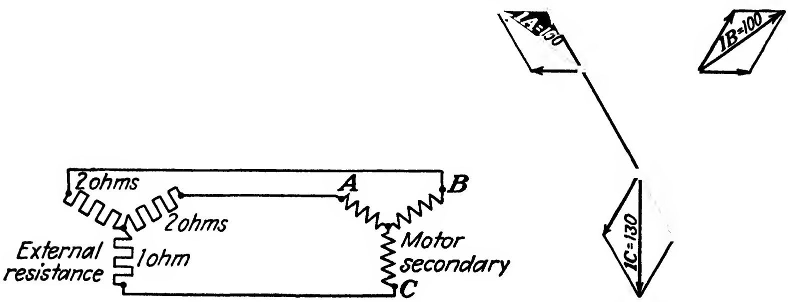


FIG. 247.—Vector diagram of current with switch No. 1, Fig. 246, closed.

simplified diagram of connections, together with a sequence table. When the motor is first started, the current in each phase of the secondary is equal and no unbalancing occurs. When switch No. 1 is closed, we will assume, the resistance in one phase is only half the value in the other two. The difference between the maximum and minimum currents in the secondary, however, is only 30 per cent. This is shown in Fig. 247. The

normal full-load current in the secondary would take an intermittent value between the 100 per cent current in two of the phases and the 130 per cent current in the third phase. The actual full-load current corresponding to this condition would be approximately 111 per cent, which represents an overload in one phase of 17 per cent. Switch No. 2 is now

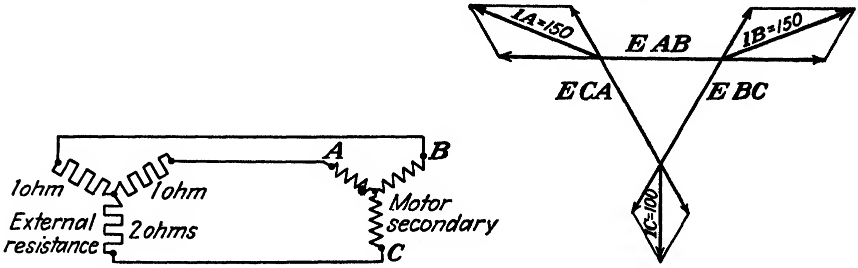


FIG. 248.—Vector diagram of current with switch No. 2, Fig. 246, closed.

closed, giving a low resistance in two phases and a high resistance in one (see Fig. 248). Assuming that the low value of current is 100 per cent, the other two phases will have current of 150 per cent. The equivalent balanced current for this combination is 135 per cent, which represents an overload of approximately 11 per cent in two of the phases.

TABLE 4.—OPERATION OF 40-HP. THREE-PHASE 60-CYCLE 220-VOLT INDUCTION MOTOR WITH VARIOUS VALUES OF EXTERNAL SECONDARY RESISTANCE

Resistance in ohms per leg			Primary volts			Primary amperes			Equivalent balanced primary amperes (r.m.s.)	Secondary amperes			Equivalent balanced secondary amperes (r.m.s.)	Speed in r.p.m.	Pound-feet torque	Power factor
0.81	0.81	0.81	220	218	220	114.8	109.2	110.8	111.8	77.2	76.8	76	76 7	415	242	78.6
0.81	0.81	0.39	220	218	220	117.7	110	114	114	64 4	90 1	79 2	78 6	520	242	77.15
0.39	0.39	0.81	220	218	220	117	110	114	113 8	90.6	62 3	79 5	78.4	600	242	77.5
0.39	0.39	0.39	220	218	220	111.7	104	110	108.7	75 2	75.2	74 8	75.15	660	242	79.7
0.13	0.13	0.39	220	218	220	114	108	112	111.4	90.7	55.4	81.7	77.2	768	242	78.4
0.39	0.39	0.13	220	218	220	114	108	111	111.2	63	92 6	72 4	77.1	723	242	78.2

When switch No. 2 is closed, the currents in the three phases are balanced. Other values of resistance can be used and the analysis be worked out for each combination.

Unbalanced currents in the secondary cause the primary to draw a low-frequency current from the line. This is caused by the single phase component of the secondary field. B. G. Lamme[1] has explained this very

[1] LAMME, B. G., *Elec. J.*, Vol. 12, p. 394.

fully for the extreme case in which one phase of the secondary is open circuited.

The heating effect of the unbalanced currents in the secondary of the motor is distributed in proportion to the squares of these currents, the total heating being equal to the sum of the squares of the currents, thus $I_1^2 + I_2^2 + I_3^2$. In other words, the heating in the motor is distributed throughout the motor and the rating of the motor is not limited by the maximum current in any one phase. These results have been verified by actual test. The secondary loss was found to be only 5 or 10 per cent higher unbalanced than balanced (see Table 4).

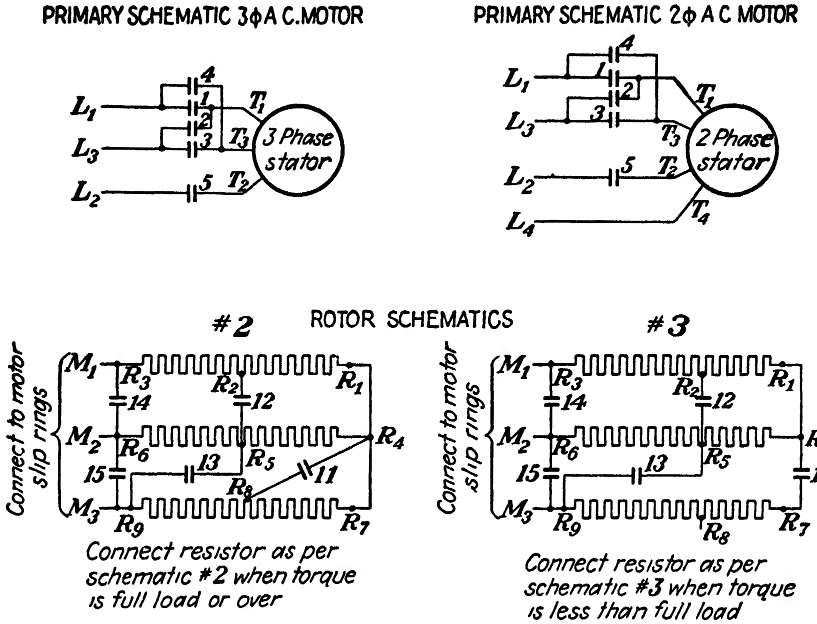
The rating of a motor of this type is dependent largely upon ventilation. When it is running at a slow speed, the fan action of the rotor is very much less than at full speed. This fan action varies as the square of the speed. The load that the motor carries depends to a considerable extent upon this fan action, and, therefore, the temperature of the motor with a given torque will be much higher at a slow speed than at the high speed. The effect of this variation in speed is considerably greater than any effect due to unbalanced currents. In applying these motors, it is, therefore, necessary to limit their torque at slow speeds. This information can be obtained from the data furnished by the motor manufacturers.

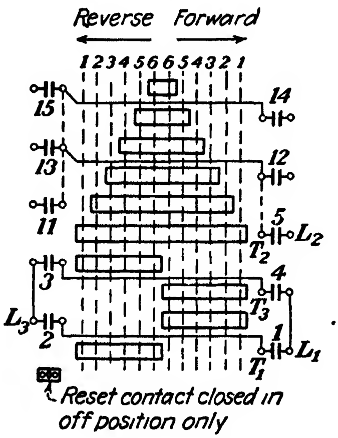
Certain applications require a low initial starting torque. This can be very readily obtained by connecting the motor secondary in single phase, leaving one leg of the resistance open circuited. Under these conditions, the motor will exert a starting torque equivalent to approximately two-thirds of the torque that would be obtained with the same amount of resistance in each leg and all three legs in circuit. Since the first notch of the controller gives a relatively low torque, not much work is being done by the motor and it is entirely satisfactory to operate, single phase. This reduces the amount of resistance required. A standard controller can be connected as shown in the diagram in Fig. 249 to give a single-phase secondary operation on the first notch. If the resistance furnished with the motor gives half full-load torque with the secondary balanced on the first notch, the controller can be reconnected to start the motor single phase and obtain a starting torque of only 33 per cent of full-load torque. This is an easy way to adjust the starting torque where a low value of resistance is required, and it reduces the amount of resistance required for a given installation.

The speed-torque characteristics of a polyphase motor operating with a single-phase secondary winding are explained in Chap. VII and illustrated in Fig. 106.

For motors of 200 hp. and larger, the secondary control may consist of a liquid controller (see Fig. 245). Each phase of the secondary of the motor is connected to a series of iron plates. These iron plates extend

down into a tank, which may be filled with an electrolyte, usually carbonate of soda and water. These plates are of different depths and so arranged that the number of plates, as well as the immersed area, increases





SEQUENCE TABLE

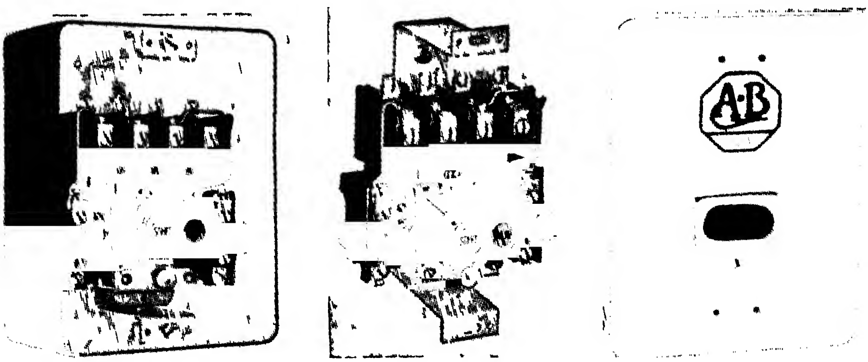
Sw	Reverse 6	5	4	3	2	1	Off	Forward 1	2	3	4	5	6
1	O	O	O	O	O	O							
2								O	O	O	O	O	O
3	O	O	O	O	O	O							
4								O	O	O	O	O	O
5	O	O	O	O	O	O		O	O	O	O	O	O
11	O	O	O	O	O				O	O	O	O	O
12	O	O	O	O						O	O	O	O
13	O	O	O								O	O	O
14	O	O										O	O
15	O												O

FIG. 249.—Cam controller

as the water level rises. By the proper proportioning of these plates the desired acceleration can be obtained. In Fig. 245, the iron plates or electrolytes extend into the upper tank, while underneath is a larger tank used for storing and cooling the electrolyte. A centrifugal pump, driven by a small motor, lifts the electrolyte from the lower into the upper

tank. A valve, or weir, in the upper tank can be adjusted to give any desired level and is operated by the same lever that operates the master switch. A master switch controls contactors in the primary of the motor. A movement of the operating lever in either direction first operates the master switch to close the primary circuit of the motor with a small amount of electrolyte in the upper tank. A further movement of the lever increases the height of this electrolyte until full speed of the motor is obtained. The pump has only a limited capacity, so that an appreciable time elapses between the movement of the weir and the increase in the height of the electrolyte; this time element can be adjusted so that the minimum period of acceleration is fixed at a safe value. The weir is large enough to permit the electrolyte to discharge very rapidly, so that when the lever is thrown quickly from the forward to the reverse direction the electrolyte will be at approximately its minimum level when the primary switches are reversed. The continual pumping of the electrolyte from the lower tank to the upper tank and the discharge through the weir causes a rapid circulation and dissipates the heat energy with a minimum amount of steaming.

The advantages of the liquid controller are (1) its simplicity, (2) its large thermal capacity, which enables it to sustain heavy overloads for short intervals of time, and (3) the absence of definite notches or steps, so that absolutely smooth acceleration is obtained. In this country there has been little demand for this form of controller in small sizes, partly because of a prejudice against the use of liquid and partly because the other forms of controllers are usually cheaper for small motors.



a b c

FIG. 250.—Allen-Bradley full voltage starter for a small squirrel-cage induction motor. Arranged for mounting in a plastered wall. In *a*, the starter is mounted within its enclosure, *b*, the starter mechanism is on its mounting bracket; *c*, is the cover plate.

SQUIRREL-CAGE MOTORS

Full-voltage Starters.—Many squirrel-cage motors are started by connecting the primary to the power supply without external current-

limiting means. Such starters consist of a three-pole magnet contactor (for three phase) operated by a push button. Thermal overload relays are usually provided as they have enough time delay to remain closed during the starting period and yet be set low enough to protect the motor

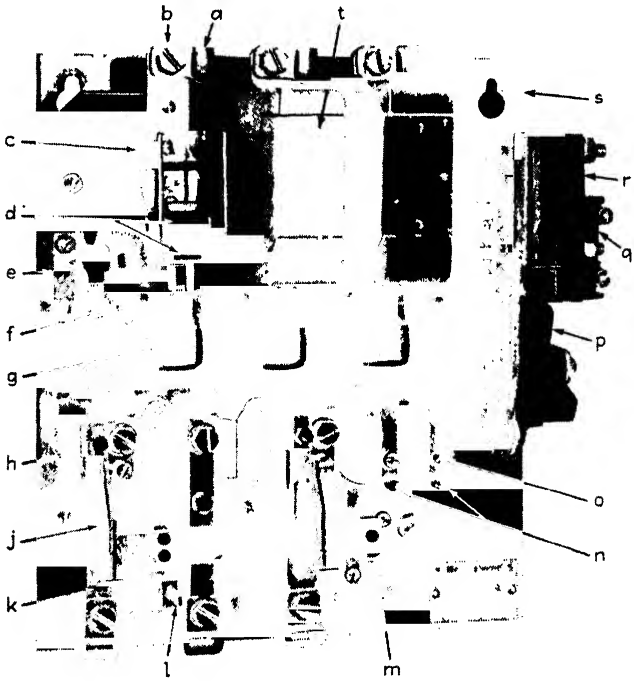


FIG. 251.—Westinghouse 100-amp. linestarter of unit for a squirrel-cage induction motor. *a*, Unit assembly on steel panel. No back or panel wiring. For "built-in" applications. *b*, Accessible "right-angle" terminals can be turned in any direction for most convenient wiring. *c*, Arc-box support also serves as blow-in coil to force arc quickly into "deion" arc quencher. *d*, Arc box removed to show heavy duty copper contacts. *e*, Large bearing with nitrided shaft. *f*, Shunts located to prevent localized bending. *g*, Long contact springs—no appreciable change in contact pressure as contacts wear. *h*, Overload relay. *j*, Heater removed to show straight bimetal strip. *k*, Ample contact area for heater terminals prevents localized heating. *l*, Reset push rod. *m*, Quick-break silver contacts on overload relay. *n*, Control-circuit terminals. *o*, Electric interlock with double-break silver contacts. *p*, Vertical operation of the magnet prevents accidental closing from mechanical shock or tilting. *q*, Coil. *r*, E-shaped magnet. *s*, Entire assembly can be removed from cabinet by taking out three accessible machine screws. *t*, "Deion" arc box.

from continuous overload. The branch-circuit protection takes care of short circuits. The motor current at start will be from four to six times full-load current, but it lasts only 1 or 2 sec. It drops rapidly as the motor speed increases. A momentary drop in voltage may affect the lights, but the drop will not be enough to be noticed where a substantial power supply is available.

Public-service companies limit the size of motor that can be started in this way from their network systems, depending upon the motor location. Motors are available that have reduced starting current at full voltage.

Fractional horsepower motors are started with a manual switch having a thermal overload trip. These motors are usually single phase. Motors of 1 hp. and larger are usually three phase.

The current taken by an induction motor in starting can be limited by placing resistance in series with the primary and using a short-circuited

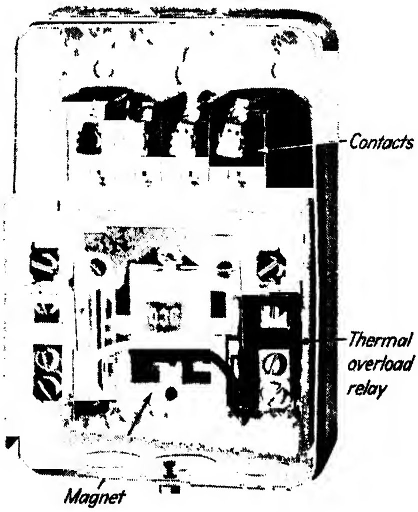


FIG. 252.—General Electric 2-hp. starter for squirrel-cage motors with two thermal relays, Fig. 294.

secondary. This form of secondary is commonly known as a squirrel-cage secondary and the motor is spoken of as a squirrel-cage motor. If resistance is used in series with the primary, the current will be reduced in proportion to the resistance inserted. The torque of the motor, however, will decrease as the square of the voltage across its terminals. This method of starting (see Fig. 257) is very simple and inexpensive and is often used with small motors. There are a few applications for large motors that will require 90 per cent of normal voltage to start, where this form of starter would be more satisfactory than the transformer type. The maximum current is taken at the time the motor starts from rest, and this current gradually decreases as the motor increases in speed, so that the voltage on the terminals of the motor will gradually increase, as the drop through the resistance is proportional to the current.

Autotransformer Starters.—Many squirrel-cage induction motors are started by using a transformer to apply a reduced voltage to the primary of the motor. The advantage of a transformer over a resistor is that the reduced voltage is obtained with little or no loss in power,

FIG. 253.—General Electric oil-immersed three-pole magnetic switch for use in corrosive atmospheres or exposed to the weather. This switch is provided with two overload relays (Fig. 295) and interlocks for low-voltage protection. It can be used as a full-voltage starter for squirrel-cage motors or as a line switch for any type of control. *a*, Tank lowered; *b* tank raised in place.

and therefore the current drawn from the line is less than the current taken by the motor in the ratio of the starting voltage to the line voltage. The connections commonly used for this type of starter are shown in Fig. 258. The transformer has only one winding and is usually called an "autotransformer." The complete device is often called an "autostarter" or a "compensator."

The relative values of current in the different circuits during starting are shown on the diagram, not including losses in the transformer. These values of current are given merely to bring out the saving in power that results from this method of starting. The starting voltage is assumed to be 65 per cent of normal, which gives approximately 42 per cent of the torque that the motor would exert at standstill, if it were connected to full voltage. This starting torque of the motor at full voltage is usually from 150 to 200 per cent of full-load torque, so, at 65 per cent of line voltage, the starting torque would be from 65 to 85 per cent of full-load torque, which is sufficient to start most loads. Other taps are provided on the transformer so that the starting voltage may be adjusted.

FIG 254 —An oil-immersed push-button station enclosed in a cadmium-plated cast-iron case with wide metal-to-metal flanges between the oil tank and the top cover The contacts, under oil, are operated by a lever and a shaft that extends through the case in a tight-fitting joint Thus the station is suitable for use in highly corrosive atmospheres, and it is also weather resistant

Figure 259 shows a vector analysis of the voltage and current in one of the phases of an autotransformer starter assuming 80 per cent of line voltage applied to the motor terminals. The same analysis is given in Fig. 260 for a starter using resistance to reduce the voltage of the motor to 80 per cent of normal at the time of starting These two figures show that, for the same starting conditions, the autotransformer

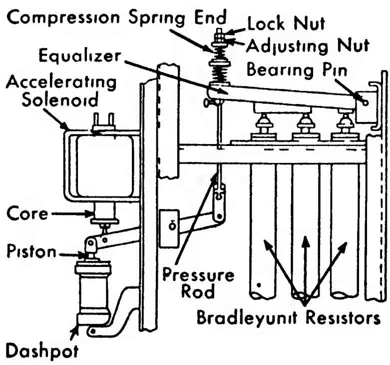


FIG 255 —Allen-Bradley accelerating solenoid, dashpot, pressure rod, and equalizing bar arrangement used on large squirrel-cage motor starters (Fig 256)

starter takes about one-third of the power from the line and about 80 per cent of the current, when starting from rest. In both cases the wattless current is the same.

If 90 per cent of the line voltage is required to start the motor, there is very little use of employing a transformer for starting purposes. Such a condition usually indicates that the motor is not suitable for the particular application; either a wound-secondary motor should be used or a larger squirrel-cage motor. The starting torque of a squirrel-cage motor can be increased by increasing the secondary resistance. This, however, decreases the efficiency of the motor. Usually the secondary resistance of a squirrel-cage motor is adjusted by using different materials in the rings short-circuiting the secondary windings and is not adjustable after the motor is built. One method of increasing the starting torque of an existing motor is to saw slots in the short-circuiting rings between the connections to the winding bars. Where the motor is used for continuous operation and requires heavy starting torque, it is undesirable to use a high-resistance secondary, therefore the wound-secondary motor is preferable.

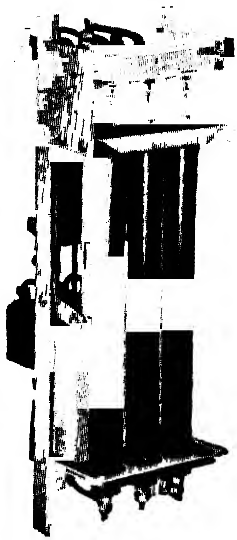
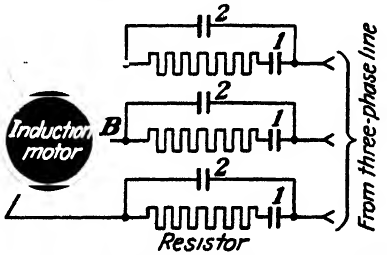


FIG. 256.—Rear view of Allen-Bradley Company automatic two-step resistance starter intended for three-phase service showing the three Bradleyunit resistors. The desired resistance value is obtained by means of an adjusting screw and equalizing bar which operates the pressure plugs at the tops of the tubes (Fig 218). Construction permits removal of the starter from the cabinet as a complete unit.

A commercial starter for small and medium-sized motors is shown in Fig. 261. The switch in the lower part of the case is immersed in oil. Above the switch is the transformer, and in front of the transformer is located the overload protection. In the Off position the handle stands central. To start the motor, the handle is moved in the direction that closes the contacts marked 1 in Fig. 258. After the motor has accelerated to approximately full speed, the handle is moved in the opposite direction and the contacts, which are marked 2, are closed. The handle is held in this position by a small magnet called the "low-voltage coil," which releases the handle on the failure of



SEQUENCE OF SWITCHES

Sw	Run	
1	O	
2		O

FIG 257.—Connections for starting a squirrel-cage motor by series resistance.

voltage and allows it to return to the Off position. A latch is usually pro-

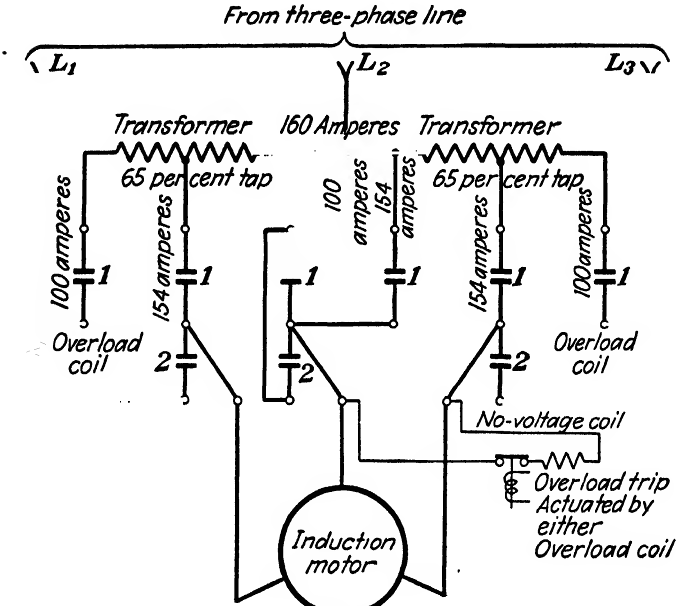


FIG. 258.—Connections for starting a squirrel-cage motor by an autotransformer starter. In the starting position contacts 1 are closed. In the running position contacts 1 are open and contacts 2 are closed. The amperage given is for the starting position only and is merely relative. The no-voltage coil serves to hold the handle in the running position against the action of a spring that returns it to the Off position if the voltage is interrupted or reduced below a certain value. Either one of the overload coils will interrupt the circuit of this no-voltage coil.

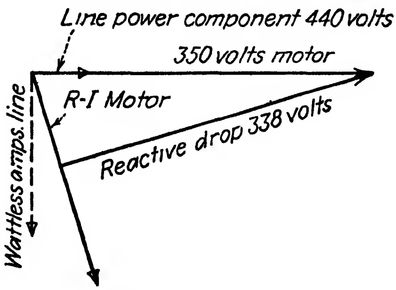


FIG. 259.—Single-phase diagram[1] of circuit with autotransformer for starting to give 80 per cent of line voltage at the motor terminals, rotor-locked conditions.

Motor characteristics: resistance 0.9 ohm; reactance 3.2 ohms; impedance 3.32 ohms. Wattless current 80 amp: power taken from the line 10 kw.; line current 84 amp.

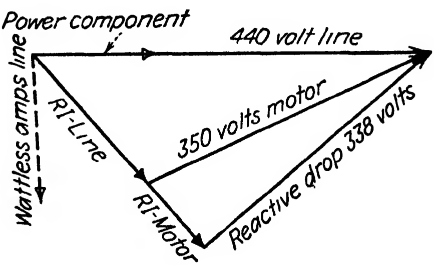


FIG. 260.—Single-phase diagram[1] of circuit, with resistance for starting, to give 80 per cent of line voltage at the motor terminals, rotor-locked conditions.

Motor resistance characteristics: resistance total 2.68 ohms; reactance 3.20 ohms; impedance 4.18 ohms. Power taken from the line 29.6 kw.: wattless current 80 amp.; line current 105 amp.

[1] The diagram shows the advantage of using a transformer instead of a resistance for squirrel-cage motor starting. A similar diagram with 65 per cent of line voltage at the motor terminals shows that the power taken from the line is nearly five times that taken with an autotransformer and the current 30 per cent greater. The transformer characteristics are neglected in the above analysis.

vided to prevent the operator from accidentally throwing the handle into the running position first.

In passing from the starting to the running position with this arrangement, it is necessary to open the connections, so that the motor will not be

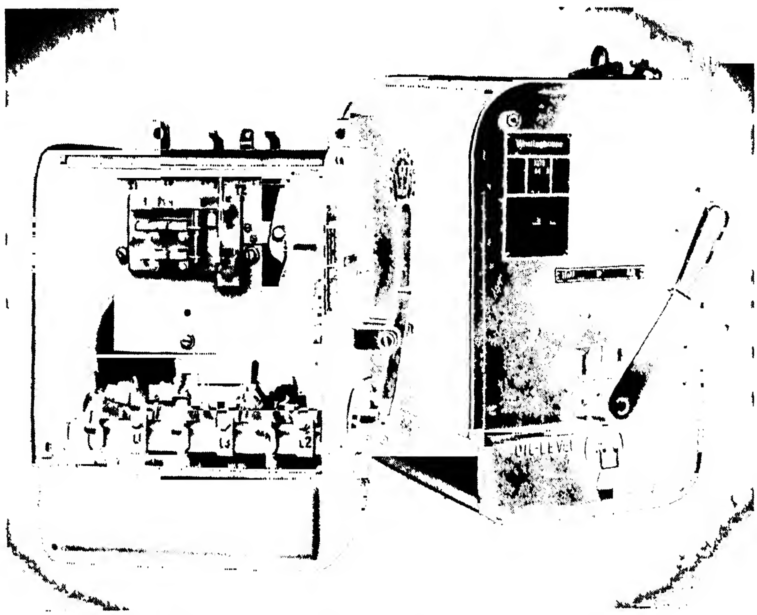
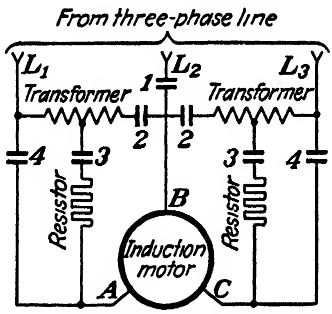


FIG. 261.—Westinghouse autotransformer starter for squirrel-cage induction motors.



SEQUENCE OF SWITCHES

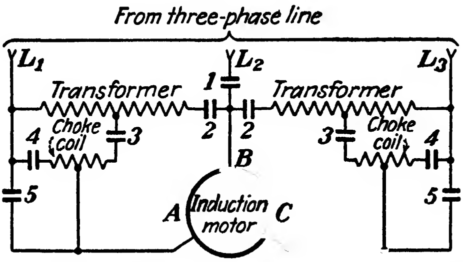
Sw	Run		
1	O	O	O
2	O	O	O
3	O	O	
4		O	O

FIG. 262.—Connections of autotransformer starter with resistor to obviate opening the circuit when changing from starting to running positions.

connected to the starting tap on the transformer and at the same time connected to the line, as this would short-circuit a section of the transformer and probably destroy it. In starting large motors, it is often

desirable to pass from the starting to the running position without opening the motor circuit. This may be done by using a resistance connected as in Fig. 262. This resistance is inserted between the starting tap and the line to prevent short-circuiting the transformer at the time the connections are changed. In this arrangement the contacts marked 2 and 3 represent the starting connections. They are not opened until after contacts 4 are closed.

Where several starting steps are used, the arrangement shown in Fig. 263 may be made. This makes use of a small autotransformer,

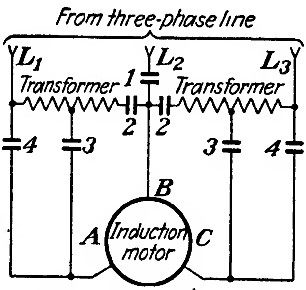


SEQUENCE OF SWITCHES

Sw.	Run				
1	O	O	O	O	O
2	O	O			
3	O	O			
4		O	O	O	
5				O	O

FIG. 263.—Connections for multipoint starting with an autotransformer.

the center of which is connected to the motor load. After the autotransformer is energized, contact 3 of this auxiliary coil is connected to the starting tap. One-half of the coil then acts as a choke coil and gives the minimum starting voltage. When contact 4 is closed, an intermediate voltage is obtained. Contact 3 is then opened and 5 is closed,



SEQUENCE OF SWITCHES

Sw.	Run		
1	O	O	O
2	O	O	
3	O	O	
4		O	O

FIG. 264.—Modified method of producing multipoint starting with an autotransformer.

which connects the motor directly to the line, giving the final step in starting. This method makes a very simple set of connections for a magnetic-contactor starter where a multipoint starter is required.

A modification of this arrangement is shown in Fig. 264. This arrangement is similar to that of Fig. 258 but the switches are operated in a different manner. The contacts marked 1, 2 and 3 are first closed.

This gives the same connection as closing contacts 1 in Fig. 258. If contacts 2 are now opened, one end of each autotransformer is disconnected from the line and the motor is left across the line with a part of the transformer winding in series, which acts as a choke coil. Switch 4 is immediately closed, connecting the motor to the line. This short-circuits a section of the transformer but, since the winding is not energized, no harm results. Switch 3 is now opened, disconnecting the motor from the transformer.

Disconnecting the primary of an induction motor from the line when passing from the starting point to the running position makes very little difference with small motors. With large motors, however, in special cases, it may cause surges of current and voltage.[1] These surges are more likely to occur in high-speed than in slow-speed motors. They depend, however, upon the characteristics of the motor and can readily be taken care of by the manufacturer when he furnishes the motor and the starter as a combined unit.

The distribution of current within the windings of an autotransformer starter is somewhat involved, but an approximate analysis omitting minor factors is interesting and explains certain features that are not apparent without such an analysis. We will first consider the exciting current, or "magnetizing" current, as it is sometimes called. It is composed of two principal items, the magnetizing current, which is a zero power-factor current, and the iron-loss current, which is a 100 per cent power-factor current. These two elements give a resulting current, which is called the "exciting" current and which may have a power factor as high as the power factor of the induction motor when it is connected to the line and the rotor is stationary.

By referring to Fig. 265 it will be noted that the exciting current in the longer section of the autotransformer tends to flow in opposition to the motor-load current. Since these two currents have power factors that are not far apart, the motor current neutralizes this magnetizing current, and it is possible so to proportion the motor-load current that there will be very little current or I^2R loss in the larger part of the transformer windings. This condition in only approximated, as the motor current is not exactly in phase with the exciting current. It illustrates, however, the fact that the magnetizing current actually reduces the I^2R loss in the larger part of the transformer windings. The two currents add in the small end of the transformer winding so that, as the starting voltage is decreased, the effect of this magnetizing current becomes more and more apparent. The current taken by the motor, however, decreases with the

[1] This is brought out in Hellmund's paper, Transient Conditions in Asynchronous Induction Machines and Their Relation to Control Problems, *Proc. A.I.E.E.*, February, 1917.

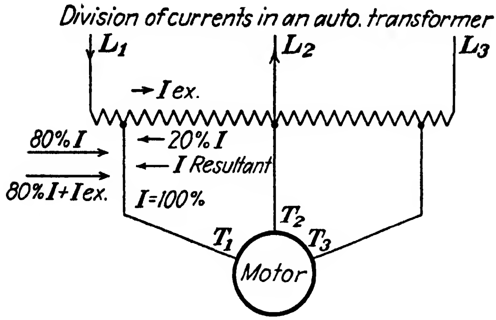


FIG. 265.—How the exciting current cancels out the load current in the larger part of the autotransformer winding. (*I* is load current. *Iex* is excitation current of the transformer.) The load current represented as 100 per cent divides in proportion to the tap ratio. In the case shown with the 80 per cent tap, 20 per cent of the load current tends to flow through the large number of turns and 80 per cent through the small number of turns. The exciting current and the load current in the large number of turns oppose. During starting, when the power factor of these currents is approximately equal, they subtract almost directly. The net resultant current, therefore, in the large number of turns is small and the consequent heating effect even smaller, since the heating varies as the square of the current. These currents add in the small number of turns, but since this is a heavy winding designed to carry load current, the additional heating effect is small. The same effect takes place if the autotransformer is connected on the 65 per cent tap.

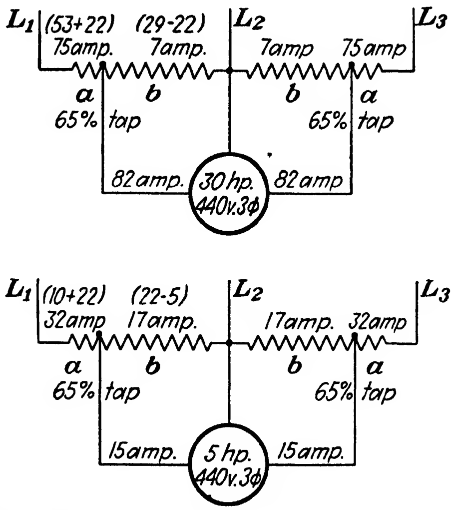


FIG. 266.—A 30-hp. autotransformer starter connected to 65 per cent of the normal voltage. The distribution of current during the starting period based on the root-mean-square value of the motor current during acceleration. It is assumed that the exciting current is 22 amp. and approximately in phase with the motor current. This assumption is not strictly correct as the phase angles of the various components of the current are unsymmetrical and the current values do not add or subtract directly. The current components also differ in each of the two phases. The diagram is made approximately correct for purposes of illustration and, therefore, does not take into account the minor differences enumerated above.

decreasing voltage, so that one effect offsets the other to a considerable extent.

The distribution of current in an autotransformer during the starting of the motor is further illustrated by Figs 266 and 267. We will assume that the autotransformer starter has been designed for a 30-hp. three-phase 440-volt motor and that the root-mean-square current of this motor per phase during acceleration is 82 amp. when connected to 65 per cent of normal voltage (see Fig. 266). We will also assume that the exciting cur-

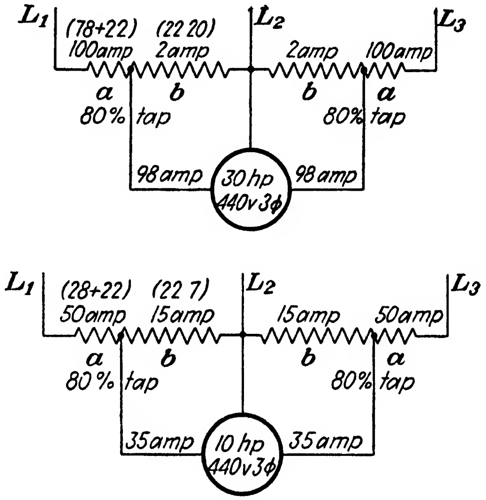


Fig 267.—A 30-hp autotransformer starter connected to 80 per cent of the normal voltage The distribution of current during the starting period based on the root-mean-square value of the motor current during acceleration It is assumed that the exciting current is 22 amp and approximately in phase with the motor current This assumption is not strictly correct as the phase angles of the various components of the current are unsymmetrical and the current values do not add or subtract directly The current components also differ in each of the two phases The diagram is made for purposes of illustration and is, therefore, only approximately correct and does not take into account the minor differences enumerated above

rent of the transformer is 22 amp. The motor current is divided between section *a* and *b* of the transformer, as follows: section *a*, 53 amp. and section *b*, 29 amp. In section *a*, the two currents add, making a total of 53 plus 22, or 75 amp. In section *b* of the transformer the currents subtract, making a total of 29 minus 22, or 7 amp. Since section *b* represents 65 per cent of the total winding, it is seen that the total heating in the transformer is reduced by the exciting current. If the motor is connected to the 80 per cent tap (Fig 267), the heating in the transformer will be still less, although the motor current is greater. This is because section *a*, which carries the extra current, is only 20 per cent instead of 35 per cent of the total winding space. This point has been demonstrated by actual tests.

Let us now assume that the 30-hp. starter was used for starting a 5-hp. motor, three-phase and 440-volt. The full-load current of this motor is approximately 15 amp. when connected to 65 per cent of normal voltage. This motor current is distributed in the transformer windings as follows: section *a*, 10 amp. and section *b*, 5 amp. We assumed above that the exciting current was 22 amp. The total current in section *a* will, therefore, be 10 plus 22, or a total of 32 amp., as compared with 75 amp. for the 30-hp. motor. The current in section *b* will be 22 amp. minus 5, or 17 amp. total as compared with 7 amp. for the 30-hp. motor. The heating effect of the current in section *b* is, therefore, about six times as great for the 5-hp. motor as for the 30-hp. motor. If the 5-hp. motor is connected to the 80 per cent tap, the difference will be still greater.

These two examples show that a large starter used on a small motor may heat up more than it will if used with the motor for which it is designed. The two previous examples are exaggerated and the currents do not cancel to the full extent shown, because of the differences in phase angles, as the examples are simplified to make them easy to follow. In making applications of starters to smaller motors, care must be exercised. It is evident that if the exciting current were zero or had a very small value, an advantage would be gained by using a large starter with a small motor in the same way that a resistor will heat up less with a small motor than with a large one. This, however, makes a very poor transformer when used with a motor to the full horsepower rating. The exciting current should be made high enough to reduce materially the heating on the 65 or the 80 per cent tap.

From time to time, some one measures the exciting current of an autotransformer starter at no load and is surprised to find it quite large. This is true, and the heating effect will naturally be considerable if it is left on long enough. If this test is carried a little further and the motor is connected to the circuit with its secondary locked in a stationary position and the input current both from the line and in the motor is accurately measured, it will be found that, by decreasing the motor current in the ratio of the transformation and subtracting this from the total input current, the magnetizing current has added in many cases less than 5 per cent to the total current. This is true of the 65 per cent tap. If these tests are now repeated on the 80 per cent tap, the increase in the total current on account of the magnetizing current will be found to be still less.

Another way to analyze the problem is to consider that the magnetizing current taken by the motor is fixed for a given voltage. The autotransformer furnishes this magnetizing current to the motor. If we consider the section of the transformer between the motor terminals, we will find that the magnetizing current required by the transformer is approximately 180° out of phase relation with the magnetizing current

taken by the motor. This results in the magnetizing current of the one canceling that of the other. If these magnetizing currents are equal, there will only be a small flow of current in this section of the transformer resulting from a difference of phase relation between the currents.

The section of the transformer winding between the motor terminals and the line and designated as section *a* in Figs. 266 and 267 has a magnetizing current flow through its windings that is not neutralized by the magnetizing current of the motor. The two magnetizing currents add vectorially and tend to heat these windings, owing to the I^2R loss. If the resistance of this portion of the winding is kept low, the actual wattage loss is also low, this being only a question of design.

Let us now consider the current taken from the line. This is made up of two components, one the energy component and the other the magnetizing component. If the magnetizing current of the motor subtracts from the magnetizing current of the transformer in section *b* (the long section), the heating effect in this section is comparatively small. By proper designing of the short section of the transformer winding (section *a*) so as to keep down the I^2R loss therein, the total loss in the complete transformer can be made quite low. This condition is obtained by having the transformer exciting current approximately equivalent to the exciting current of the motor, and it holds good for only one particular size and design of motor. In the designing of commercial autotransformers, it is necessary to select a certain range of motor sizes and speeds and to select a motor-magnetizing current that represents the average value and then to make the magnetizing current of the transformer equal to this value. The windings of the transformer must be proportioned for the worst condition, which is obtained in section *a* of the winding when the largest motor is being used and in section *b* of the transformer winding when the difference between the motor-magnetizing current and the transformer-magnetizing current is a maximum. An additional allowance must also be made for small differences in phase angles.

It will be seen from the above that the exciting current of a properly designed autotransformer for intermittent starting should be much larger than that for power transformers. This excess magnetizing current will overheat section *b* of the transformer winding if it is left on for any considerable length of time without the motor load, because there is no cancellation of current in this section of the transformer winding.

The exciting current varies with the voltage and the frequency. Each time the magnetism in the iron reverses, it generates a voltage in the transformer windings. The product of this magnetism multiplied by the number of turns in the coil multiplied by the frequency must balance the line voltage. Since the number of turns in the coil has a fixed value for a particular design, an increase in voltage at a constant frequency would

require a corresponding increase in magnetism in order to balance this increased line voltage. If the voltage remains constant and the frequency decreases, an increase in magnetism would be required to make the product constant. When the iron in the autotransformer is worked pretty hard, as is the case in the starting transformers, an increase in magnetism requires a considerable increase in exciting current, the iron loss going up quite rapidly at this part of the magnetization curve. Therefore, any unusual increase in voltage or decrease in frequency will cause a proportionally larger increase in the exciting current. Standard autotransformers are designed and guaranteed to operate successfully on 10 per cent variation in the line voltage, provided that the frequency remains constant. The converse is also true, *viz.*, if the line voltage remains constant, the frequency may vary 10 per cent. This, however, is a rather unusual condition.

The torque of an induction motor varies as the square of the voltage. It is usual to express the starting characteristic of an induction motor by stating that it has a certain locked torque. This is the torque exerted when the rotor is stationary and normal voltage is applied to the primary windings. This torque is usually expressed in terms of the full-load torque. Thus, a motor having a locked torque of two means that the torque at zero speed is equal to twice full-load torque with normal voltage on the primary. If 70 per cent of voltage were applied to the motor primary, the motor would exert a torque equivalent to 2 multiplied by $(7/10)^2$, or 98 per cent of full-load torque. The torque at any other starting voltage can be obtained by expressing this voltage in percentage, squaring it, and multiplying by the locked torque given in per cent of full-load torque.

This starting torque is independent of the method employed for obtaining the reduced voltage. Sometimes the claim is made that a certain motor will start with one style of starter and not with another, the inference being that the starters have different effects on the starting torque of the motor. This is true only if the starters provide different voltages at the motor terminals. The taps on an autotransformer are usually expressed in percentage of full voltage. These percentage ratios are not exact, as it is necessary to compensate for the voltage drop through the transformer. This compensation differs with different motors, owing to the variation in the starting current. It is, therefore, improbable that two different makes of autotransformers would give exactly the same voltage at the motor terminals; this is probably the explanation of the failure of one type to start the motor, while the other was successful. The difference in voltage may seem trivial, but it must be remembered that this difference is squared and that a little extra torque may be all that was required to break the load from the static position and allow

the motor to start rotating. As soon as the motor commences to rotate, the friction decreases and the torque of the motor gradually increases, so that the critical period is the instant of starting from rest. Sometimes the torque of a motor varies slightly when starting from rest, depending upon the location of the rotor slots relative to the primary winding. While this variation of starting torque is usually quite small, it may be appreciable in particular motors and, therefore, should be taken into consideration in comparing starters.

The starting voltage can be adjusted by changing the starting connection from one transformer tap to another. Standard transformers provide for 65 per cent and 80 per cent taps. This gives 42 per cent and 64 per cent locked torque of the motor when starting.

TABLE 5.—TEST ON A 100-HP 220-VOLT 60-CYCLE THREE-PHASE MOTOR WITH A TYPE *A* AUTOSTARTER, SHOWING VOLTAGES AND STARTING TORQUES OF THE MOTOR WITH BALANCED AND UNBALANCED TAP CONNECTIONS

Test on 65% tap, motor locked

	Line volts		Volts at motor terminals	Motor torque
	No load	With load		
L_1-L_3	230	199	118.5	
L_2-L_3	229	196	120	278 lb.-ft.
L_1-L_2	229	194	122	
Test with one winding connected on the 65% tap and the other on the 80% tap				
L_1-L_2	229	190	130	
L_2-L_3	229	184	141	340 lb.-ft.
L_1-L_2	229	193	121	
Test with 80% tap				
L_1-L_2	229	188	141	
L_2-L_3	229	185	139	410 lb.-ft.
L_1-L_2	229	188	141	

These tests show that the transformers in V connection give nearly balanced voltages with unbalanced taps. The starting torque obtained with unbalanced taps is approximately the average of the two torques that would be obtained with either balanced connection.

Where intermediate values of starting torque are necessary, they can be obtained by connecting one starting lead to the next higher starting tap; for instance, if one side is connected to the 65 per cent tap and the other side to the 80 per cent tap, an intermediate value of starting torque will be obtained with an intermediate value of power input. Connections of this kind unbalance the phase so that more current is taken from one

phase than from the other. The amount of this unbalancing, however, is considerably less than the difference in voltages after the motor begins to revolve. In no case is the current taken from either phase greater than would be taken if both leads were connected to the higher voltage. Table 5 gives the results of a test made with both balanced and unbalanced connection and shows the torques and voltages at the motor terminals.

TABLE 6.—COMPARATIVE TEST ON A THREE-PHASE 60-CYCLE SIX-POLE SQUIRREL-CAGE MOTOR SHOWING STARTING TORQUE WITH AUTOTRANSFORMERS IN OPEN V AND IN Y, 100% OF RATED VOLTAGE APPLIED TO TRANSFORMER WINDINGS

Motor torque	Three transformers in Y connection	Two transformers in open V connection
At 65% voltage	33.5% of locked torque	33.1% of locked torque
	34.3% of locked torque	34.0% of locked torque
At 80% voltage	52.0% of locked torque	51.7% of locked torque
	52.4% of locked torque	52.2% of locked torque

The use of two autotransformers in a V connection for starting three-phase motors is sometimes criticized, on the ground that it produces unbalanced voltages at the motor terminals and, therefore, decreases the starting torque of the motor. The tests in Tables 5 and 6 show that there is very little unbalancing and that the amount is negligible. The torque exerted by the motor in starting from rest is practically the same as with the three-transformer arrangement. The variations in the starting torque exerted by different motors of the same design, because of irregularity of manufacture, are considerably greater than the effect of slight unbalancing.

The National Electrical Manufacturers Association has agreed that the standard starting period for manually operated autotransformer starters shall be 15 sec. This is simply an arbitrary designation and means nothing unless a careful study is made of the effects of starting on the transformer. It does not mean that, if the starting period exceeds 15 sec. for one start, the transformer will be injured.

About 1912, the National Board of Fire Underwriters agreed with the manufacturers to use an arbitrary "stand" test for autotransformer starters. This test consisted in connecting the line wires to full voltage and applying three times full-load motor current to the starting tap, the starting tap to be selected from 40 per cent to 65 per cent of line voltage. With these connections, the line voltage was impressed on the starter for 15 sec. every 4 min. The remaining 3¾ min. were allowed for the transformer to cool. This test was repeated for 1 hr., which is equivalent to 15 starting periods, and was based on the assumption that the heating effect in the starter was equivalent to that which would occur in starting

under abnormal conditions. The test under these extreme conditions was to determine the probability of a starter's becoming a fire hazard.

Since that time, manufacturers have been designing their autotransformers to meet this test without being destroyed.

It should not be assumed, however, that a commercial starter can be applied where it is necessary to start as frequently as is indicated by this test. Standard starters may be used for accelerating motors where the starting period is approximately 15 sec., and not over six or eight starts are made without allowing the transformers to cool down to the room

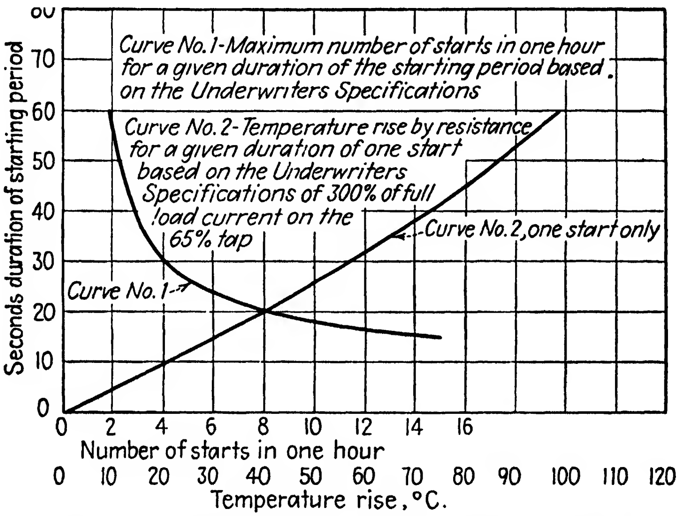


FIG. 268.—Temperature rise under different starting conditions.

temperature. Several starts of a longer period, even as long as 30 sec., can be made if the transformer is cold and the starts are not repeated too often. The curve in Fig. 268 indicates the relative increase in temperature under different starting conditions.

Many starters can be used on other voltages and frequencies than those for which they are rated; but, in making such interchanges, it should be remembered that we have three elements to consider:

1. The autotransformer.
2. The low-voltage coil.
3. The overload relay.

The low-voltage coil is independent of the size of the motor, but it is sensitive to changes in voltage or frequency, as the excess voltage will cause it to overheat and on a low voltage it will fail to hold. When there is a decrease in voltage together with a decrease in frequency, these will counterbalance each other. For instance, a 550-volt 60-cycle coil operates successfully on a 460-volt 50-cycle circuit.

The autotransformers should not be used on voltages more than 10 per cent in excess of the normal rating, but they may be used for any voltage of less value, provided that the current of the motor does not exceed the normal value for that particular transformer. For instance, the 30-hp. 440-volt autostarter can be used with a 15-hp. 220-volt motor by changing the low-voltage coil. It is obvious that, if the current value is kept the same, the overload relay will not be affected. If the frequency is decreased, the voltage should also be decreased; for example, the 550-volt 60-cycle transformer can be used on a 440-volt 50-cycle circuit for a motor that is smaller than the rating of the transformer proportionally to the decrease in voltage.

If the frequency is above normal, as in the case of a 25-cycle starter being used on a 40-cycle circuit, the transformer will still be satisfactory; and, if the size of the motor is kept the same, the same starter can be used by changing the low-voltage coil. The low-voltage magnet is provided with a brass shading coil for 60-cycle and a copper shading coil for 25-cycle circuits, so that a change in frequency over this range may require a change in the shading coil if the best results are to be obtained.

Automatic acceleration for a.c. controllers at present is usually limited to the series-relay method or a time-element method. The time-element method is very satisfactory where the timing device can be relied upon. For rapid acceleration and reversing service, the series relay method is very good.

CHAPTER XVIII

SYNCHRONOUS-MOTOR CONTROL

Synchronous motors are used because they can correct the power factor, as well as drive machinery. The synchronous generator is one of the oldest forms of electric machinery and is fully described in textbooks and well understood by electrical engineers. The synchronous-motor construction is identical with and has the same characteristics as the generator, except that the operation is reversed. Alternating-current electric power is supplied to the primary of the synchronous motor and converted into mechanical work by the rotation of the motor. Power-factor correction is obtained by adjusting the strength of the d.c. field. A separate source of power is required for furnishing the d.c. supply to the field

METHODS OF STARTING SYNCHRONOUS MOTORS

More care is required in starting a synchronous motor than an induction motor because the former must be brought into synchronism with the a.c. supply circuit. During the starting period it is usually necessary to manipulate the field and other circuits and it is, therefore, safer and better to use an automatic controller than a manual controller.

The torque required for starting the motor from rest and bringing it up to synchronous speed is obtained by means of damper windings, which function in the same manner as the secondary of a squirrel-cage induction motor. The primary is connected to the source of supply at full voltage or at a reduced voltage by means of an autotransformer. The primary winding develops a rotating magnetic field, which induces a current in the damper windings. The reaction between these windings exerts a torque that accelerates the motor. The damper windings are useful for obtaining stable operation of the motor after it has been synchronized; they eliminate hunting, or a tendency for the speed of the motor to oscillate above or below synchronism.

The starting torque of these motors is approximately the same as that of a standard induction motor having the same number of poles. It is practicable to build synchronous motors for much lower speeds than induction motors. Increasing the number of poles of synchronous motors increases the size for given horsepower ratings but does not introduce any serious difficulties in the electrical design. On the other

hand, a large number of poles in the primary of an induction motor causes excessive leakage and poor power factor. For this reason, low-speed motors are usually of the synchronous type. The starting torque of the low-speed synchronous motor is low, on account of the large number of poles required to give low-speed operation. Four- or six-pole synchronous motors will exert considerable torque at starting.

The torque limitations of a synchronous motor occur as the motor approaches synchronous speed. An induction motor operates at several per cent below synchronism, the difference in speed, or the slip, of the motor generating a sufficient voltage in the secondary to circulate the current necessary to develop the torque required by the load. When the synchronous motor reaches 2 or 3 per cent of synchronous speed, the torque necessary for pulling the motor into synchronism is obtained by energizing the d.c. field magnets. These magnets react on the primary and develop an oscillating torque. This torque is positive during most of the cycle, the period of negative torque being short. The closer the motor is to synchronous speed, the longer is the period of positive torque. This oscillating torque swings the rotor into synchronism and locks it in at this speed.

If full field strength is applied when the motor is running at too low a speed, the proportion of negative torque will be much larger and may be sufficient to prevent the motor from accelerating to full speed. When a direct connected exciter is used, it may be practicable to close the circuit of the field windings through this exciter when the synchronous motor starts from rest, if the starting load is light, as the d.c. machine is self-excited and does not build up its voltage until the motor has approached full speed.

The method of handling the field circuit of the synchronous motor differs for motors of different designs. In order to obtain the best results, it is necessary to cooperate with the motor designer and select the arrangement of field circuits that will give the best results.

When the primary, or stator, is connected to the line and the secondary, or rotor, is stationary, a 60-cycle rotating magnetic field is set up in the rotor. This causes current to flow in the grids or damper windings on each pole face, which exerts a torque to start the motor and accelerate it in the same manner as an induction motor. It also induces a voltage in the field windings, which should have the circuit closed through a resistor to prevent the development of an excessive voltage in these windings. At start, as in an induction motor, the current will be heavy, the power factor and the impedance low, and the rotor frequency the same as the primary. The current decreases, the impedance and the power factor increase, and the secondary frequency decreases with increase in speed. At 90 per cent of speed, the current drops rapidly and the impedance

increases inversely as the current. The secondary frequency decreases to zero at synchronous speed.

The motor pulls into synchronism when unlike poles of the primary and field windings are opposite each other; therefore, the least power disturbance is caused if the d.c. field is built up as the unlike poles approach each other. The change in field frequency, primary current, or primary impedance is used by different manufacturers to initiate the closing of the field circuit. It is desirable to accelerate the motor to its maximum speed as an induction motor, before energizing the field to keep down the momentary primary-current increase that occurs at this time. This maximum speed depends upon the motor load, which will be different from time to time. The controller should delay closing the field circuit until the motor has accelerated as far as possible (probably 2 or 3 per cent of synchronous speed), but should connect the field as soon as the motor has reached a balancing speed. Automatic means for doing this at the right speed and when unlike poles are approaching will be described.

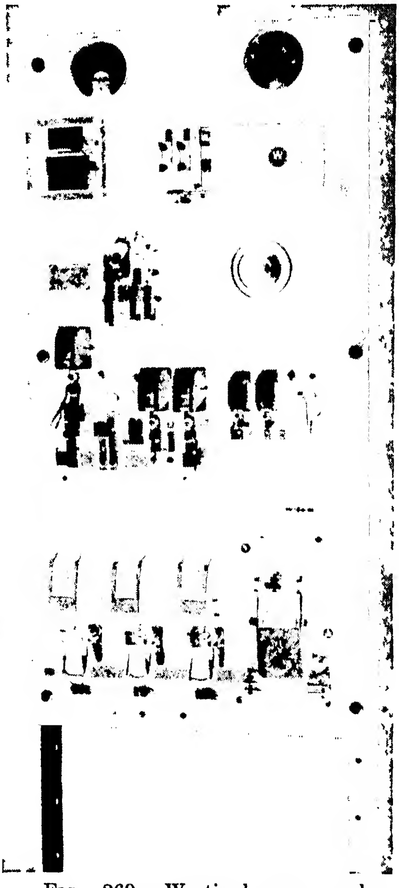


FIG. 269.—Westinghouse synchronous motor controller, using the definite time method of acceleration.

The smaller motors, particularly the slow-speed ones, can be started with a light load at full line voltage and with very simple means for closing the field circuit. When the line disturbances must be kept to a minimum, an exact method for energizing the field and for obtaining reduced voltage starting or starting on a part winding of the motor must be used. A relay responsive to primary current can be used to transfer the primary windings from the starting control to the device for establishing running connections, as the current drops rapidly above about 90 per cent of speed.

The reduced-voltage methods for starting induction motors explained in Chap. XVII can be used, or the part-winding method (see Fig. 276) can be applied to motors having this type of winding. Some of the

methods for automatically energizing the d.c. field windings will now be described.

The Field-frequency Method.—When the motor is at rest and the field circuit is closed upon itself through a resistor, the rotating field set up by the primary of the motor will cause an alternating current to flow

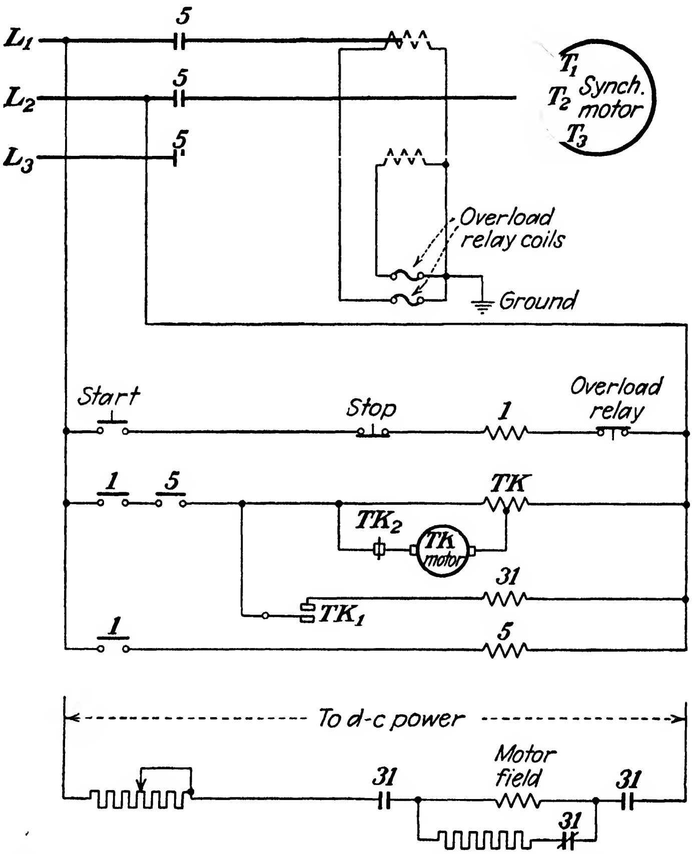


FIG. 270.—The time-delay synchronous motor controller. The Start button closes switch No. 1, this closes switch No. 5 and starts the synchronous motor TK. After a fixed time, TK_1 closes which closes switch No. 31 and energizes the d.c. motor field. TK_2 then opens and stops motor TK. Power-factor relay and instruments have been omitted from the diagram to make the motor connections easier to follow.

in the closed field circuit, owing to transformer action. When the rotor is at rest, the frequency in the field circuit will be the same as the line frequency. As the motor increases in speed, the frequency of the field circuit decreases but the maximum current remains substantially constant. As soon as the rotor reaches 2 or 3 per cent of synchronous speed, the current in the field circuit drops very abruptly, as is shown in Fig. 271,

and can be used to operate automatic means for changing the motor connections from starting to running.

The Electric Machinery Manufacturing Company uses a polarized field-frequency relay (see Fig. 271), which operates on the drop in field current when synchronism is nearly reached. They describe the operation of this relay as follows:

In Fig. 271, 1 and 2 illustrate the magnetic fluxes in the polarized field-frequency relay.

In 1, when the induced field current in coil *B* flows in one direction, the flux of this coil opposes the flux of d.c. coil *C* to force the combined strong resultant

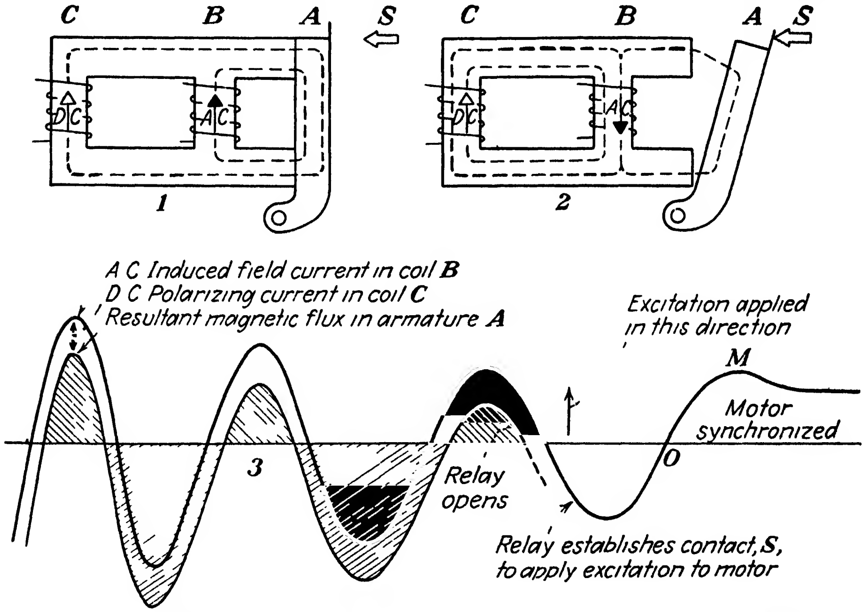


FIG 271.—Operation of the field-frequency relay used by the Electric Machinery Manufacturing Company for accelerating synchronous motors (see Fig 272 for wiring diagram)

flux through the armature *A* of the relay. This condition is that which occurs during the lower shaded loops of 3. In 2, when the induced field current in coil *B* is reversed, the flux of coil *B* combines with that of coil *C* so that the resultant flux through relay armature *A* is relatively weak, as shown by the smaller upper shaded loops of 3.

The effect of the d.c. polarizing coil *C* of the relay, therefore, is to make the magnetic flux in the relay armature *A* unsymmetrical with respect to the zero line of the induced-field-current wave. Thus the relay armature cannot open in the portion of the induced-field-current wave spanned by the large lower loops of relay-armature flux. The relay armature will open only in the portion of the induced-field-current wave spanned by the small upper loops of relay armature flux.

The induced field current in relay coil B decreases in amplitude as the motor reaches synchronizing speed, and an upper shaded loop of relay armature flux is reached as is shown in 3, where the relay armature A will no longer stay closed. The relay then drops open to establish contact S to apply excitation to the motor field at the point indicated on the induced-field-current wave.

The time of opening of the relay depends partly on the retarding pull of the relay flux. When set to open at lower synchronizing speeds (92 to 94 per cent) an air gap between the armature and the core causes the relay to open more quickly than when set to open at higher speeds with less relay air gap. Hence the field contactor always closes at the same favorable point on the induced-field-current wave.

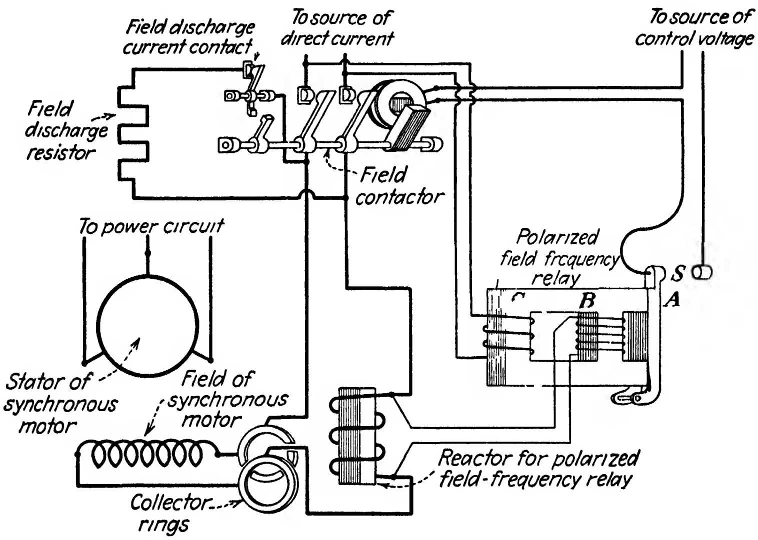


FIG. 272.—Wiring connections of the field circuit for the polarized field-frequency relay of Fig. 271 (see text for description).

The excitation is applied in the direction shown by the arrow, opposite in polarity to that of the induced field current at the point of application. This is done to compensate for the time required to build up excitation caused by the magnetic inertia of the motor-field winding. The inertia is such that the d.c. excitation does not become appreciably effective until the induced current has reversed at O, in 3, to the same polarity as the direct current. The excitation continues to build up, synchronizing the motor at M, which represents the approximate normal relative positions of the rotor and stator poles of the motor when running in synchronism.

During starting, a current, induced in the field winding of the synchronous motor (Fig. 272) and declining in frequency as the motor accelerates, flows through the field-discharge resistor, the reactor, and coil B of the polarized field-frequency relay. The magnetic core of the relay has a d.c. coil on leg C, an induced-field-current coil on leg B, and a pivoted armature A with contact S. Coil C connected to the source of d.c. excitation establishes a constant magnetic

flux in the relay core that polarizes the relay. Superimposed on the magnetic flux in the relay core, caused by d.c. coil C, is the alternating magnetic flux produced by the alternating induced-field current flowing in coil B. The armature A thus carries the sum of the two fluxes produced by coils B and C on one-half cycle of alternating induced-field current, and a much smaller amount of flux on the other half cycle.

At the moment of starting the motor, the relay armature A snaps to the closed position shown in Fig. 272, opening the contact S. Up to the synchronizing speed of the motor the flux through the armature of the relay is enough to keep the armature closed. The reason for this is that the reactor across which coil B is shunted has a relatively high voltage drop, whereas the reactance of relay coil C is relatively low. Hence at all except very low frequencies of the induced-field current enough current will flow through relay coil C to hold the relay armature closed. As the motor accelerates, however, the induced field current declines in frequency and an increasingly larger portion of it is diverted from the relay by the reactor until at 93 to 98 per cent synchronizing speed, depending on the synchronizing speed the relay is set for, the reactor shunts enough current from coil C to permit the relay armature to open.

Since the relay in Fig. 272 is polarized by coil B, the relay armature opens only when the magnetic fluxes of coils B and C are of certain relative strength and in opposition. The design of the relay is such that this opening will take place to establish contact S, and thus close the field contactor to apply excitation at the favorable point for synchronizing.

Another method of accomplishing this is to provide a double-throw contactor having two magnets. The upper magnet is energized from direct current and tends to close the upper set of contacts; the lower magnet has its windings in series with the field. The contactor normally has the lower contacts closed and the lower magnet circuit connected in the motor field. In starting, the voltage inducted in the field windings maintains the lower contacts closed by means of the magnet. When the motor nearly reaches synchronous speed, the lower magnet is almost deenergized, owing to the induced voltage in the field windings approaching zero. This permits the magnet at the top of the contactor to overcome the pull of the lower magnet and to open the lower contacts and close the upper contacts, in this way initiating the necessary connections for changing the controller from the starting to the running position, but does not ensure that the connection will be made at the most advantageous instant. It is suitable for small motors.

The Speed-and-time Method.—The control for energizing the field has been combined by Westinghouse in an automatic motor-driven relay. An element responsive to the drop in primary current, when the motor is nearly at synchronizing speed, starts the relay motor. At this speed the rectified primary current taken from a current transformer is represented by a wavy line, shown in Fig. 274. The low part of this curve occurs

when primary and secondary poles are opposite each other. The coil of a spring-closed contact member is connected in this rectified-current cir- . There is low tension in the spring when the relay motor starts, but the spring tension is gradually increased by cam action as the relay motor

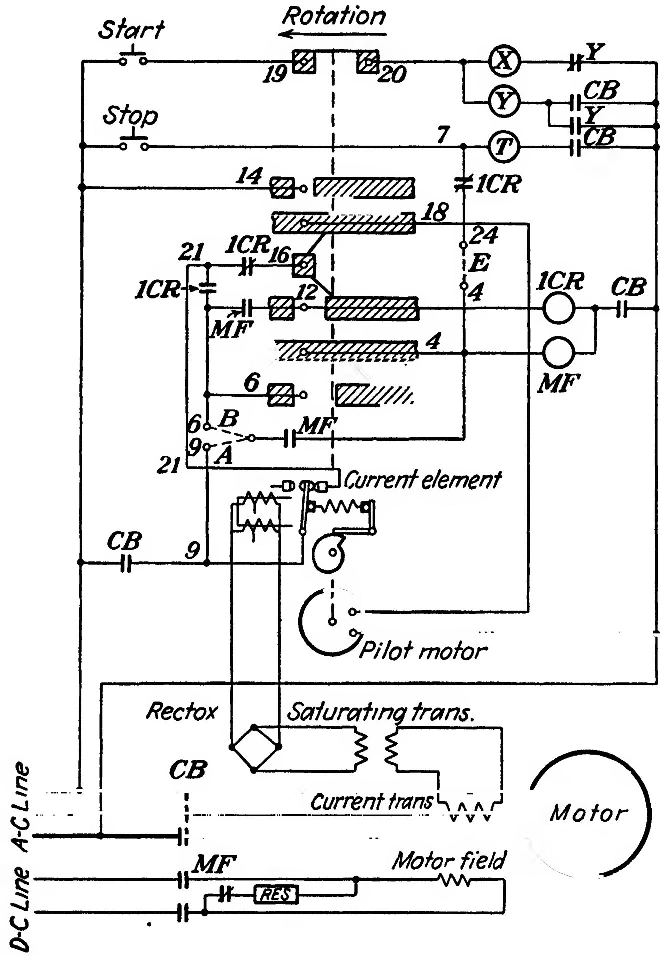


FIG. 273.—Westinghouse STA controller for full-voltage starting of a synchronous motor (see text for description, p. 265).

operates. After a few seconds the spring tension overcomes the magnet, when the current curve is in one of its valleys. The relay contacts then close and energize the motor fields at a favorable time to build up the field, as unlike poles approach each other. The relay continues to operate until it has returned to its initial position, ready for another start. The few seconds required to build up tension in the spring allow suffi-

cient time for the synchronous motor to reach its maximum speed before its fields are energized.

In Fig. 273 with the motor running or shut down, the position of the STA elements will be as shown, *i.e.*, fingers 4, 16, 18, 19, 20 will be "made," 6, 12, 14 will be "open," and spring tension on the current element will be maximum. The contacts 19 and 20 guarantee that the primary breaker cannot be closed unless the elements are in the position shown (the Off position) since these contacts interrupt the circuit to the *X* and *Y* closing relays in all other positions. Jumper *B* is closed; *A* and *E* open.

To start, push the Start button that energizes relays *X* and *Y* and closes the primary breaker. Instantly, the current element picks up to

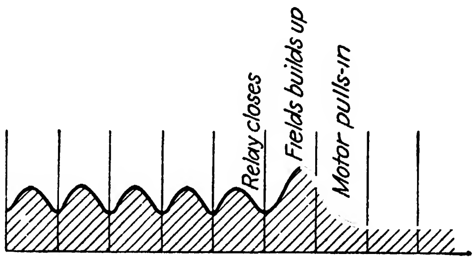


FIG. 274.—Rectified primary current during the acceleration of a synchronous motor showing where relay applies the d.c. field.

break contact 9-21 as the result of current inrush to the motor. When the inrush current drops to about 50 per cent of the initial inrush value (90 per cent speed), current element contact 9-21 closes and completes a circuit to the pilot motor through 1*CR* contact 21-16 and drum fingers 16 and 18. After a short initial movement, finger 14 "makes" and connects the pilot motor across the line so that the movement continues. The second circuit to "make" is finger 12, causing relay 1*CR* to pick up. At approximately the same time, the current element calibrating cam releases the spring tension, so that contact 9-21 again opens. After 9-21 has opened, finger 6 "makes." As the spring tension is gradually restored, 9-21 will close to complete a circuit to field contactor *MF* through 1*CR* contact 21-6. Once *MF* has closed, a holding circuit is established, either through jumper *A* to the line or through jumper *B*, *MF* contact 6-12, and fingers 12-14 to the line. These holding circuits by-pass current element contact 9-21 until the drum returns to the Off position, so that transient operations of the current element attendant to application of excitation do not trip *MF*.

With jumpers *A* and *E* in place and *B* removed, the motor will shut down if current element contact 9-21 opens as a result of pull-out. The opening of 9-21 trips relay 1*CR* and the contact 7-24 closes, energizing

the circuit-breaker trip coil. With jumper B in place and A and E removed, the motor will resynchronize in the event of pull-out. The opening of 9-21 trips both $1CR$ and MF, but the breaker does not trip since the jumper E is not in place. The $1CR$ contact 21-16 closes to start the STA unit through a sequence when 9-21 recloses, the same as occurs when the motor reaches 90 per cent speed during a normal start.

The saturating transformer is not always included. It will be used when there is a possibility of obtaining heavy short-circuit currents in

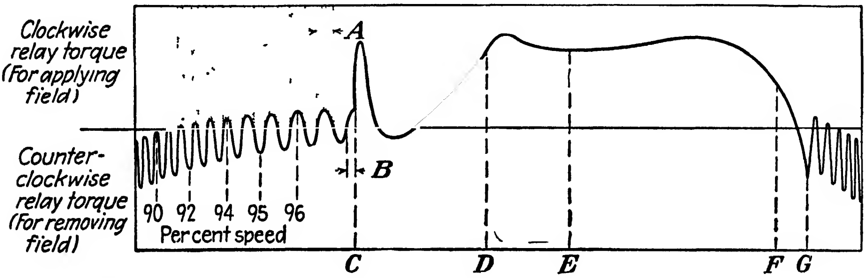


FIG. 275.—Action of SCI control during pull-in and pull-out in a General Electric Company system. (1) *Impedance changes.* As the motor accelerates, the stator impedance changes as follows: *a*, average impedance increases; *b*, frequency of cyclic variations decreases. (2) *Relay responds.* As acceleration continues, SCI relay torque responds as follows: *a*, relay torque reverses momentarily; *b*, relay contacts oscillate with torque reversals; *c*, frequency of reversals decreases; *d*, time interval of relay-torque reversal increases, as shown, by rapidly widening shaded areas. (3) *Speed is selected.* When the speed-selective time interval increases to the present value *A*, the associated timing relay operates, thus indicating that the correct synchronizing speed has been reached. (4) *Angle is selected.* After present angle-selective time interval *B* has elapsed in next cycle, the field is applied at *C* with a favorable angular relation between the rotor and the magnetic field of the stator. (5) *Motor pulls in.* During the interval *C-D* the motor pulls in. The field-applying circuit is maintained during the synchronizing interval while the rotor attains its normal synchronous relation. (6) *Synchronous operation.* The motor carries normal load in synchronism from *D* to *E*. The relay torque reflects rotor oscillations that are quickly damped out by squirrel-cage winding. (7) *Overload pull-out.* A heavy overload is applied at *E* and the motor pulls out of step at *F*, where the motor impedance and relay torque are changing rapidly. (8) *Field is removed.* As the relay torque reverses, the field contactor is deenergized and the field is removed an instant later at *G* to permit resynchronizing. (By a simple reconnection of control, the motor can be shut down at the same instant the field is removed.)

the case of a fault and where the switching equipment must withstand the same without injury. The saturating transformer prevents possible destruction of the Rectox.

Another speed-time device is the General Electric slip-cycle impedance relay, type SCI. The relay has a rotating element with a contact arm, which is caused to swing back and forth as a result of the torque produced by a combination of voltage and current coils as a function of the motor impedance. This causes the contact to open and close. As the synchronous motor accelerates, there is an increase in the stator impedance, as shown by the decrease in the line current.

There is also a cyclic variation of impedance at a frequency equal to twice the slip frequency. This frequency is low when the motor is close to full speed and the intervals during which the relay contact remains closed will increase. This contact energizes a time-delay relay that closes its contacts when the interval becomes long enough. The timing is adjusted so that the interval that closes this second contact occurs at the motor speed at which its field should be connected to d.c. power. This is the period *A* in Fig. 275. The time-delay relay energizes the field-circuit relay, which has sufficient time delay to close the field circuit at *C* on Fig. 275. This is the point where unlike stator and rotor poles are approaching each other and will lock together to synchronize the motor during interval *CD*.

RESYNCHRONIZING AND PULL-OUT PROTECTION

Either momentary low voltage or severe overload conditions may cause a synchronous motor to pull out of synchronism. Under these conditions the motor stalls and some protective features must be automatically provided. If the pull-out has occurred because of low voltage and the voltage recovers quickly, or if the pull-out has been caused by overload conditions that disappear promptly, the motor may be operated temporarily as an induction motor with field excitation removed, to reaccelerate and resynchronize. The inconvenience of a complete shutdown is, therefore, avoided. Under many conditions it is not possible or desirable for the motor to resynchronize, and power must be disconnected to prevent damage to the motor.

The control connections of a synchronous-motor controller can be arranged to permit either resynchronizing or removal of power when a pull-out occurs. The relays that operate to accomplish these results are the same field frequency, current, slip-cycle impedance, or power-factor relays that control the synchronizing when a normal start from rest is made.

REDUCED-VOLTAGE STARTERS

Low-line voltage interferes with the magnetic contactor performance during starting and increases the time required to accelerate the motor to full speed.

Some automatic starters that start with the d.c. field energized have a small contactor, which short-circuits the motor field rheostat or exciter field rheostat when the motor is being synchronized. This operation overexcites the field, improves the pull in torque, and reduces the current peaks when the motor is transformed from starting voltage to full line voltage. When an individual exciter is used to provide the motor-field excitation, the added contactor improves the operation of the d.c. con-

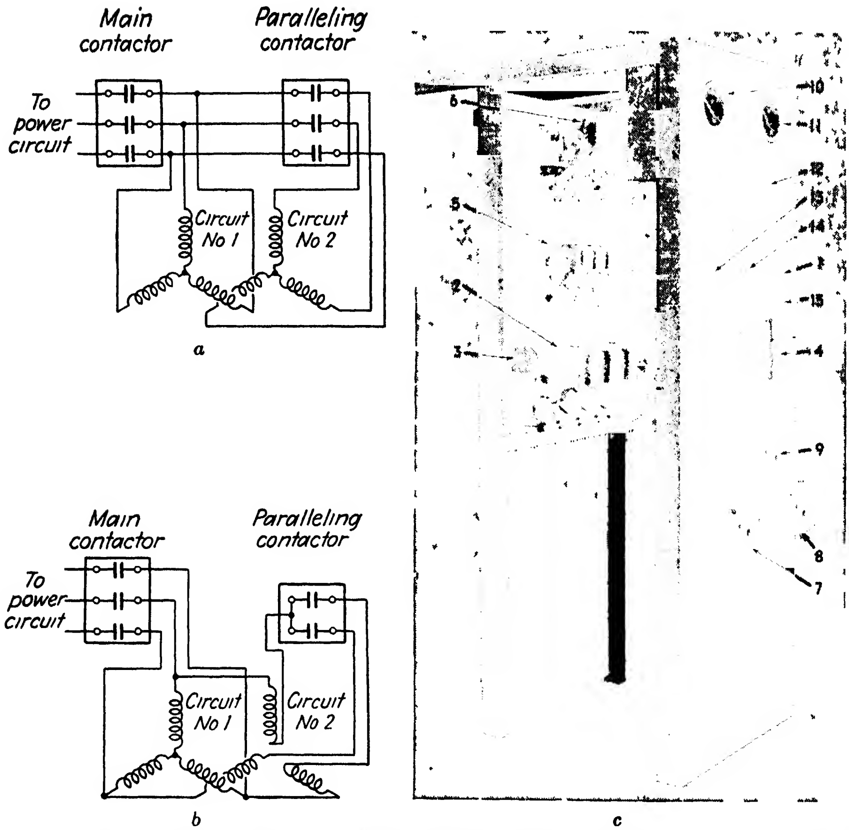


FIG. 276.—Electric Machinery Manufacturing Company automatic part-winding control for a synchronous motor driving a centrifugal pump. The control is the dead-front, two-step, air-break type. The sequence of operations of this control are given in *c*. *a*. The primary connections for the control shown in *c*. It indicates the switching means used for two-step part-winding starting. The main contactor opens both circuits in case of overload on the motor or of short circuit. *b*. Alternative connection of the second circuit by means of a two-pole contactor connected in the start of the second circuit. This cóntactor can be located near the motor if that is desirable. The main contactor opens both circuits.

c. Pressing the Run button (1) closes the main contactor (2) connecting the motor to the line on part winding. Closing of main contactor sets timing relay (3) in operation. As soon as the motor is energized, the contact of field-control frequency relay (4) opens. The motor accelerates on part winding. When a predetermined time has elapsed, timing relay operates to close paralleling contactor (5). The second circuit of the motor is then connected to the line, and the motor is then on full winding. When the motor reaches the correct speed for synchronizing, the field-control frequency relay closes its contact, closing field contactor (6). Closing of the field contactor applies excitation, obtained from the direct-connected exciter on the motor, to the field of the motor, and the motor pulls into synchronism. Overload protection while the motor is on part winding is provided by part-winding protective relay (7). Overload protection while the motor is on full winding but not yet in synchronism is provided by out-of-step protective relay (8). Overload protection after the motor is in synchronism is provided by overload relay (9). These relays all operate to open the main contactor (2), which opens both circuits of the motor. Other equipment on the control: (10) d.c. ammeter; (11) a.c. ammeter; (12) exciter field rheostat; (13) safety lockout; (14) pilot light to indicate d.c. excitation is available; (15) stop button.

tactors by having full exciter voltage impressed on the operating coils while the motor accelerates to full speed.

Low-speed synchronous motors can be started by connecting them directly to the line. The starting kilovolt-amperage with full line voltage approximates three times the normal input kilovolt-amperage. This value is no higher than that required for some of the high-speed synchronous motors started with 65 per cent of line voltage, which is the standard starting voltage when auto-transformers are used. When full line voltage is applied to a motor, the starting period is decreased approximately 60 per cent (from 1 min. to 24 sec.).

The line-voltage starter in addition subjects a synchronous motor to fewer current peaks than the reduced voltage starter of the type that opens the motor circuit at transfer from starting to full voltage, but the starting kilovolt-amperage is higher. High starting kilovolt-amperage is of less importance on large power systems, but the design limitations of the motor in some cases prohibits starting with full line voltage. When conditions permit line-voltage starting, the control equipment is simplified and the number of main contactors or circuit breakers is reduced.

THE EMERGENCY STOP

Certain applications, such as rubber and paper calenders, require means for quickly stopping machinery in case of emergency. One means of accomplishing this is to use a magnetic clutch and a magnetic brake. When the emergency occurs, the operator actuates the emergency switch that disconnects the motor from the machinery by means of the magnetic clutch; at the same time, the brake is applied, bringing the machinery quickly to rest.

Another method consists in the use of dynamic braking. When the operator actuates the emergency switch, the motor is disconnected from the line and the a.c. windings are short-circuited through a resistor. The revolving field magnets generate a voltage in the a.c. windings, which causes a heavy current to flow, converting the motor into an a.c. generator and bringing it quickly to rest. Tests have indicated that with many designs of motors the load can be stopped as quickly with dynamic braking as by the use of a clutch-and-magnet brake. Dynamic braking requires more switching apparatus, but it eliminates the clutch-and-magnet brake.

POWER-FACTOR CORRECTION

Synchronous motors, like synchronous generators, can have the field overexcited and deliver a wattless current 90 deg. in advance of the load current. This leading wattless current will neutralize an equivalent

amount of lagging current and, in this way, improve the power factor of any particular installation.

It is this ability to improve the power factor of the given installation that makes it so desirable to use synchronous motors. In order to furnish this leading current, it is necessary to build a motor larger than would be required to drive the load and it, therefore, adds to the expense of the installation to improve the power factor.

If the installation is a factory or any other large user of power having a considerable number of induction motors the amount of lagging current that would be necessary for neutralizing is considerable. Unless the loads to which the synchronous motors are attached are in large units, it may be cheaper to use induction motors for all the mechanical drives and to supply one synchronous machine running light, commonly known as "floating" on the system. The entire output of this machine can then be used for power-factor correction.

CHAPTER XIX

ELECTRON-TUBE CONTROL

OPERATION AND FUNCTIONS

The electron tube can be considered a one-way switch that is closed by heating the cathode. Negatively charged electrons are emitted from the surface of the heated cathode and travel at a tremendous speed to the anode, forming a current-carrying path (see Fig. 277). Note that

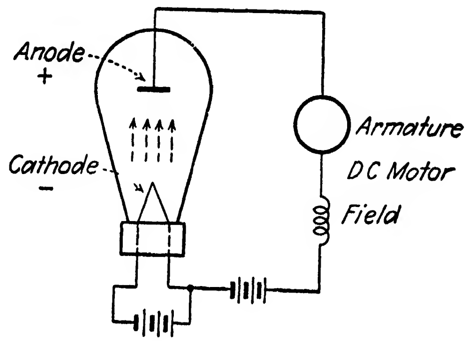


FIG. 277.

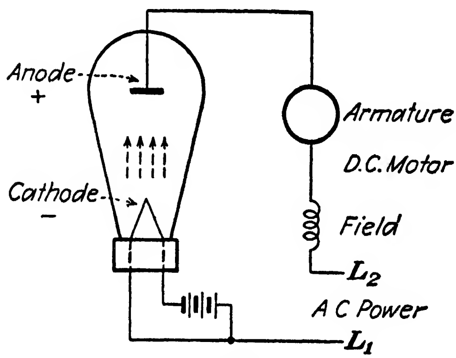


FIG. 278.

while the electron flow is from (−) to (+), the current flow in the tube is conventionally from (+) to (−). It will not flow in the reverse direction.

When we substitute a.c. power for the battery (see Fig. 278), we get an intermittent pulsating source of d.c. power through the motor, as

only one-half of the power is used. When we add a second tube and add the other half of the a.c. power wave, we can obtain full wave rectification, a source of pulsating direct current sufficiently smooth for motor-armature operation (see Fig. 279). When a shunt motor is used, two more tubes are required to energize its field.

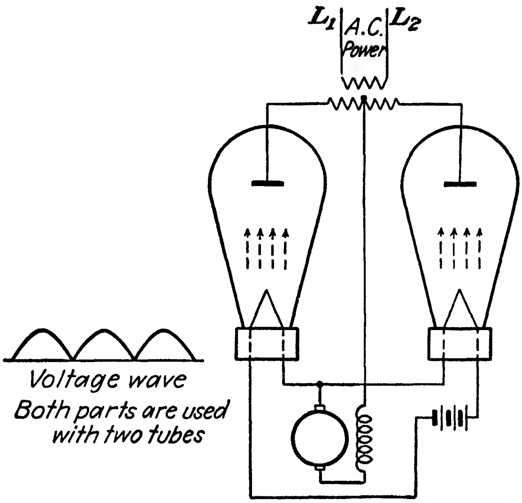


Fig. 279.—The use of two tubes to give rectified d.c. power.

Grid Control.—The armature voltage can be controlled by inserting a grid between the anode and the cathode and connecting it to a relatively low voltage; when this voltage is negative, it has a pronounced effect in reducing the number of charged negative electrons reaching the anode. When the grid is positive, the number of electrons reaching the anode is increased.

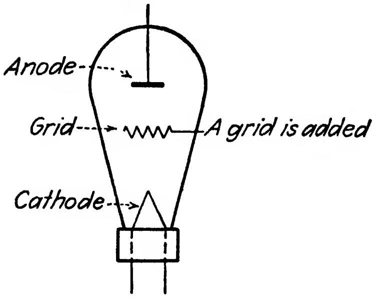


Fig. 280.

By control of the grid voltage, the voltage at the motor terminals can be changed from zero to the maximum in an infinite number of steps. The grid requires very little power and its voltage can be controlled by a small dial like that of a radio. A shunt-motor field can obtain power from a similar pair of tubes, and the field current can be changed in the same way by applying different voltages to the grid. The tube furnishes a source of variable voltage power with very little power loss.

Functions.—The tube control has three important functions:

1. Converting a.c. power into pulsating d.c. power.
2. Providing an adjustable-speed control over a wide range by adjusting the applied voltage on the armature and field coils, and by means of circuit refinements maintaining the selected speed constant from no load to full load.
3. Providing adjustable-current limit during acceleration and operation.

Conversion of Power.—The control functions of starting, reversing, dynamic brake, overload and low-voltage protection can be taken care

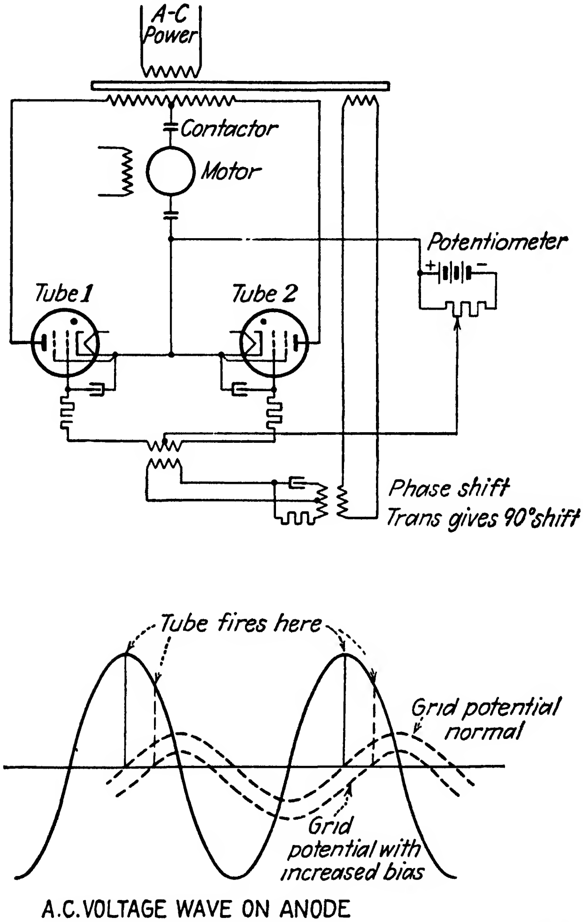


Fig. 281.—Simple form of motor control. Curve shows voltage change with grid-bias adjustment.

of by contactors in such a way that the contactor is not required to open or close the circuit under power conditions. Standard push buttons and other master switches can be used at the control position. In practice, the adjustable-voltage rectifier usually consists of two thyratron tubes for the armature circuit and two for the motor field.

The average voltage delivered by the tubes is controlled by the phase relation of their grid voltage, which is obtained from the a.c. circuit through a transformer. When the grid voltage is effectively in phase with the anode voltage, the tube will be turned full on and when the two voltages are effectively 180 deg. out of phase, the tube will be turned off completely and no current will flow. By means of varying the phase relation between these limits the tube can be turned on to any desirable degree.

Adjustable-speed Control.—The phase-shift method is the most common way of varying the output voltage of the thyratron tube. The

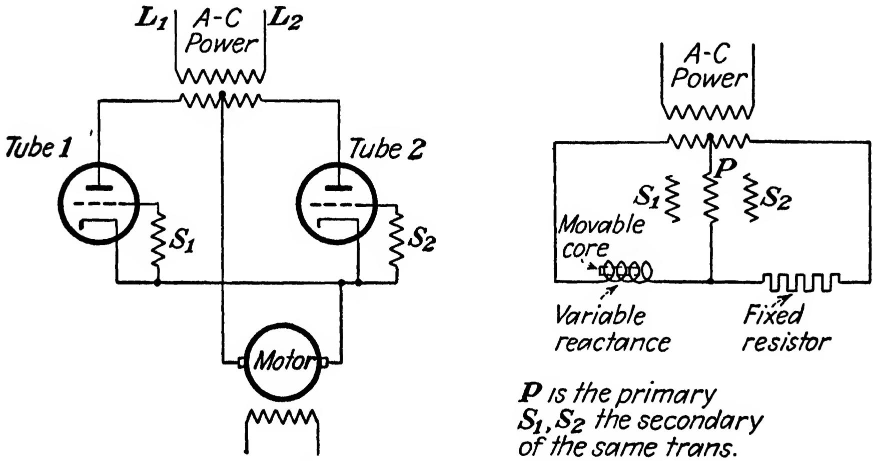


FIG. 282.—Speed control using a phase shift of grid potential wave by change of phase angle of primary windings P and secondary windings S_1, S_2.

phase shift can be obtained by a combination of a resistor and a condenser or a resistor and inductance (see Fig. 281). The phase shift can be adjusted by hand or by mechanical means, much as tension in a strip of material being fabricated or a loop of fabric can intercept a light ray (see Fig. 288) to control the motor speed. These controls can apply to either the armature or the field voltage, or to both.

Another way to shift the grid-voltage wave is shown in Fig. 282. When the variable reactance is changed, it changes the phase angle of P, which controls the secondary windings S_1 and S_2.

The curves shown in Fig. 281 give the grid-voltage wave in its normal position. The diagram shows a method of shifting the phase angle by applying d.c. voltage to the grid transformer and adjusting its amount and direction by a potentiometer control.

The speed regulation of the motor from an uncompensated tube power source will be worse than from standard d.c. power, because both the

voltage drop in the armature circuit due to the inductive reactance will be greater and because the counter e.m.f. of the motor will have to drop further with a pulsating power source, to provide voltage enough to balance the drop through the armature. This latter effect can be seen by referring to Figs. 283 and 284. The area *ER* represents approximately the voltage required to overcome the *IR* drop in the armature circuit. When the current increases, this area must increase in the same

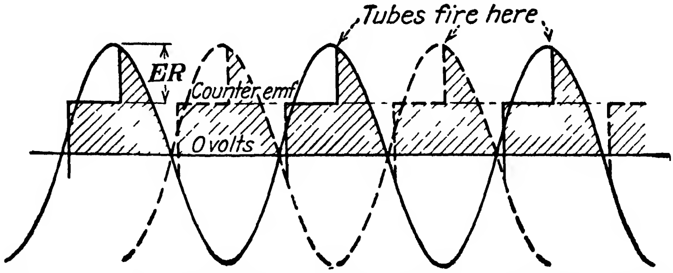


FIG. 283.—A d.c. motor operating from a tube rectifier. The shaded area *ER* measures the approximate voltage available to overcome the *IR* drop in the armature circuit. More load will increase this area.

proportion. Now refer to Fig. 284, which shows a standard d.c. voltage supply, where the area *ER* represents the voltage required to overcome the *IR* drop. If the current is doubled, the counter e.m.f. line in Fig. 283 must drop more than that in Fig. 284, to compensate for the increased *IR* drop. The drop in the counter e.m.f. line represents the drop in speed with increasing load and is greater for the pulsating, rectified d.c. power than for normal d.c. power.

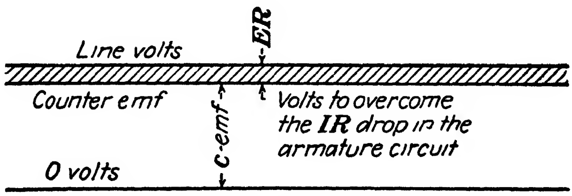


FIG. 284.—A d.c. motor operating from d.c. power *ER* is much less as the area is continuous.

This additional voltage drop can be compensated for and the motor speed can be kept constant if the phase shift of the grid voltage is automatically adjusted to a change in the motor load. This can be done by connecting the grid circuit of a small tube in shunt to a part of a resistor that is across the armature terminals, and by connecting the tube in the circuit of the grid of the power tube in such a way as to increase the voltage delivered to the motor as the load increases. So far, we have assumed a constant field from constant line voltage. The arrangement is a voltage regulator applied to the motor terminals. The speed can

be adjusted over a wide range by setting the grid circuit to regulate the voltage of the motor for the desired speed (see Fig. 286[1]).

The voltage-regulator setting must also be automatically changed to increase the voltage when the load increases, to compensate for the additional voltage drop in the armature circuit and to reduce the voltage

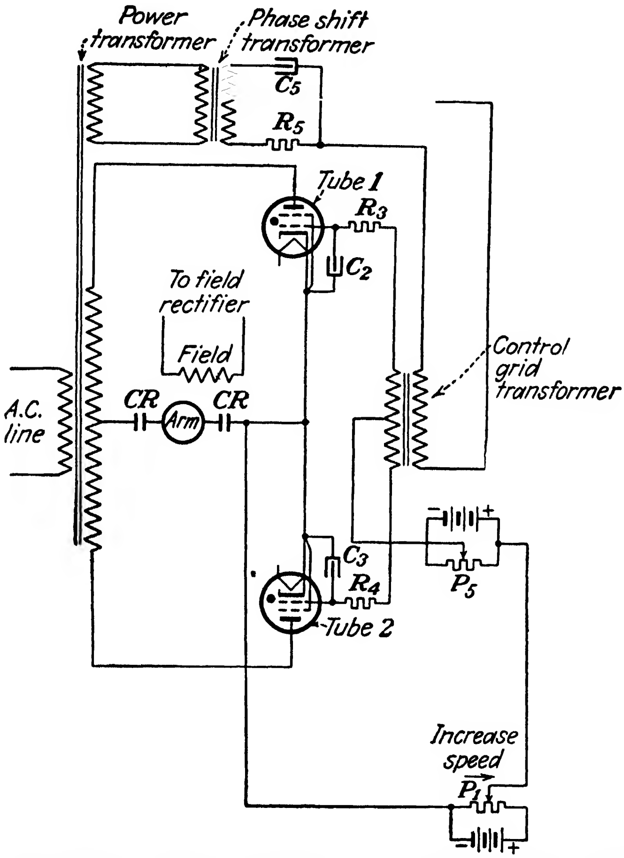


FIG. 285.—An elementary rectifier circuit for a d.c. motor without any regulating means.

when the load decreases. This change in voltage over the regulator setting is necessary to maintain constant speed. When a motor is connected to a standard d.c. system, it often has a small reverse-series field coil to weaken the field strength with increasing load. This tends to increase the speed in proportion to the drop in counter e.m.f., and one change

[1] Figures 285, 286, and 287 are taken from a paper presented by K. P. Puchlowski before the A.I.E.E. on "Electronic Control of D.c. Motors" (*Trans. A.I.E.E.*, Vol. 62, p. 870, 1943). In this paper the reasons for various control tubes are explained in detail with curves showing the motor performance under different conditions.

cancels the other to maintain constant motor speed. With tube power, a second control tube performs the functions of the reverse-series field. Its grid is connected so that the grid voltage changes in exact proportion to the load. The control tube is connected in the grid circuit of the power tubes, to increase their delivered voltage in proportion to the load and reduce this voltage when the load decreases. This control tube

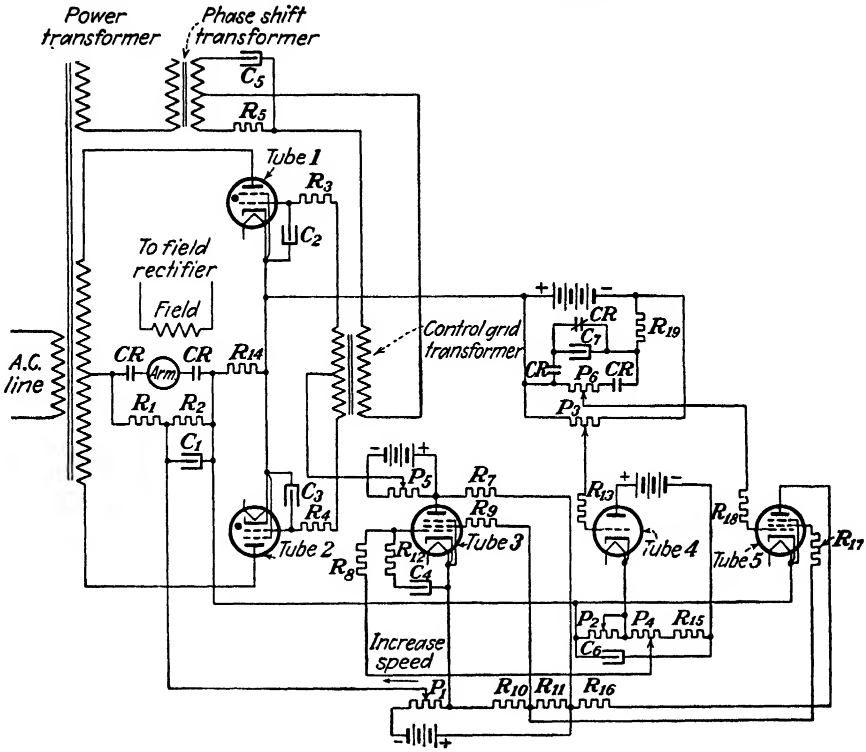


FIG. 286.—Complete diagram for a d.c. motor controller with regulating means. Tubes 1 and 2 rectify the a.c. power; tube 3 provides armature-voltage regulation, which controls the speed; tube 4 provides IR drop compensation; tube 5 provides current-limit control for acceleration and safe operating loads (see Fig. 287).

holds the motor speed more nearly constant than does the reverse-series field in a conventional motor (see Fig. 286).

Adjustable-current Limit.—Since power tubes can be injured by severe overloads, a third control tube is added, to hold the current constant during acceleration and to limit the overload current during operation. The grid of this tube is also connected so that its voltage will be in direct proportion to the armature current. The tube is inserted in the regulator-tube grid circuit to decrease the output voltage of the rectifier when the current approaches the maximum for which this third control tube is set. This gives a flat current curve during acceleration (see Fig. 287).

Parts of the Electron-tube Controller.—The electron-tube control now consists of the following parts:

1. Two power tubes, to convert the a.c. power to a source of pulsating d.c. power (see Fig. 285).
2. The first control tube, to maintain the armature voltage of the motor constant and provide means for adjusting this voltage to give a preset speed (see Fig. 286).
3. The second control tube, to increase the power voltage in proportion to the load, to compensate for the IR drop in the armature circuit (see Fig. 286).
4. The third control tube, to limit the current in the armature circuit to a preset value (see Fig. 286).

The shunt field of the motor receives power from one or two more power tubes. The field strength can be changed to give speed adjustment by controlling the grid voltage of these tubes.

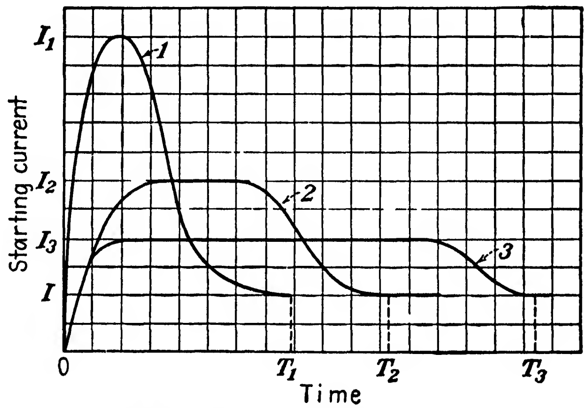


FIG. 287.—Curves showing the effect of automatic current limitation during the acceleration of the motor. Curve 1 shows the current inrush in a motor operating from a d.c. line; curves 2 and 3 show the motor current limited automatically by the electronic control to three and two times the full load, respectively. Should an operating load stop the motor, the thermal-overload relay will open the circuit.

A voltage-regulating tube can be added, if necessary, to maintain a constant preset voltage across the field coils. When field control is used to obtain higher motor speeds, a movement of the control from high to low speed causes the motor voltage to rise above the applied voltage. In the conventional d.c. system, this causes a reverse current, which reduces the motor speed quickly to the new setting of the controller. When tubes are used as a source of power, a reverse current will not flow and there is a tendency for the armature voltage to build up to an undesirable value. This can be prevented by using either an overvoltage relay of the magnetic type or by using another tube. When the mechanical load is heavy and positive, the voltage will usually remain at a safe

limit without an additional relay. This condition should be checked when the application is being made.

DEVELOPMENT FOR INDUSTRIAL USE

Tube control of power has been developing slowly for industrial applications as larger tubes are required for power circuits, and they have been expensive. A tube controller looks more like an instrument and does not get credit for its actual ruggedness. The control scheme is new to most of the users, who prefer the type with which they are familiar and that their repairmen know how to maintain. First the gas engine and now the Diesel engine have had to face this same problem, but it gradually diminishes with use.

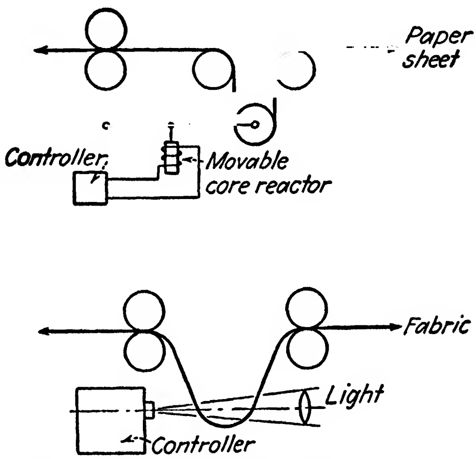


FIG. 288.—Speed control between sections of a machine.

Variable-voltage control using a motor-generator set to convert a.c. power into adjustable voltage d.c. power (see Chap. XI) has been slowly introduced—first, for mine hoists and then for reversing mill motors; later, for automatic elevators, skip hoists, reversing planer drive, and other applications. Variable-voltage control, however obtained, is the most logical way to adjust the speed of d.c. motors and, in time, will be extensively used. The electron tube can replace the motor-generator set as a source of adjustable voltage power where regeneration is not required, and it is now used for the smaller motors. It can be used to control a generator field where the power exceeds the capacity of commercial tubes or where regeneration is necessary. As the cost of tube control decreases, it will find wider use, replacing other types of adjustable speed control.

An interesting use of tubes for controlling motors is described in the latter part of Chap. VI.

PERFORMANCE AND APPLICATION

Problems to Be Met.—The performance of d.c. motors receiving power from electron-tube control is not the same as that of those operating on standard d.c. power; the principal differences are in heating and in commutation, particularly where field weakening is used to obtain greater speed range.

Heating.—The pulsating voltage from tube power causes a considerable ripple current in the armature, in addition to the average current read by a standard d.c. meter. If the meter used is an a.c. meter, which shows the r.m.s. current, the reading will be higher than that shown by the d.c. meter. The motor torque is proportional to the average current shown by the d.c. meter; therefore, the motor load must be less if the heating is kept constant. The heating is more than the square of the current increase shown by the a.c. meter. Tube power may increase the heating 40 per cent in some special cases. The increased heating is not the same for all motors. It is influenced by the inductance in the armature circuit, a factor that is not important when standard d.c. power is used. Inductance reduces the ripple current and tends to reduce the difference in heating; this inductance may be in the motor itself, or an external inductance may be connected in the circuit. Slow-speed motors have larger frames and more inductance in their armature circuits. Field circuits have so much inductance that the current is close to a constant value. When the manufacturer furnishes both the motor and the controller for a definite application, the heating factor is considered in designing the equipment.

Single-phase power causes more heating than polyphase power. Usually, the additional heating can be neglected with polyphase tube control.

Commutation.—Motors that show no sparking at their commutators on standard d.c. power may develop sparking on tube control. This is not very noticeable on small motors, but it becomes important in the larger sizes. It is more of a factor in motors operated on higher speeds by field weakening, and limits the speed range obtained in this way. This trouble will not occur if the motor is designed by the manufacturer for tube control.

Frequency.—Tube control is usually furnished for 60-cycle power and it will operate successfully on 50 cycles. At reduced frequencies, the inductive effect decreases and more ripple current may develop, so that a different design of motor and control may be necessary for 25-cycle power.

Speed Range.—Motors on tube control can be operated on a 20 to 1, even 50 to 1 speed reduction below base speed with very little difficulty,

because at this range the principal factor is armature-voltage drop, which is compensated for in the control. At very low speeds, other factors develop; they are friction, brush drop, armature slot, and torque pulsations at a multiple of line frequencies.

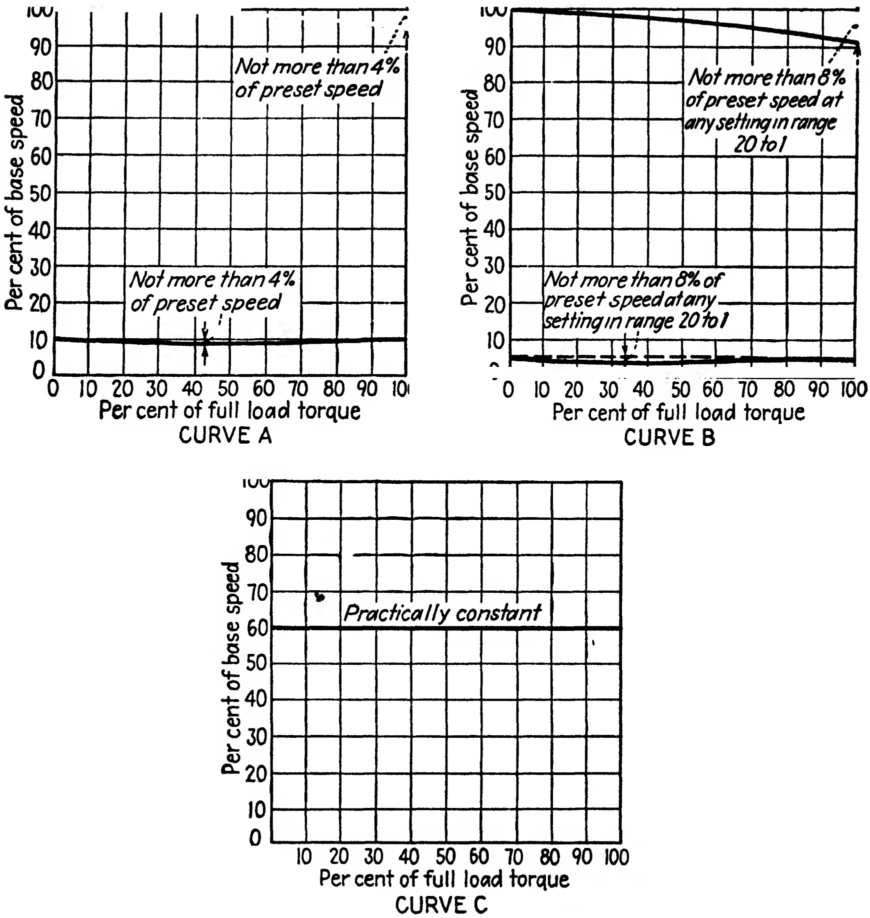


FIG. 289.—Speed-regulation curves. Percentage of base or full field speed in terms of percentage of full-load torque. Curve *A* for a 10 to 1 speed range, curve *B* for a 20 to 1 speed range, and curve *C* for constant speed at 60 per cent of base speed.

Friction can be reduced by using ball or roller bearings, and this should be done where low speeds are necessary.

Brush drop will average plus or minus 2 volts for standard motors and, with a large current, may become several times as great as the counter e.m.f. at very low speeds. Brush voltage drop is not constant and its predominating effect over the counter e.m.f. at very low speeds

is a difficult problem. This same problem occurs in motor-generator set control, where there are generator brushes in addition to the motor brushes.

The ripples in torque at low speeds caused by the armature slots can be eliminated with skewed slots, but this may mean a special motor. Skewed slots are common in many a.c. motors. Polyphase tube control materially reduces these ripples.

The torque ripples resulting from the pulsating power supply do not constitute a very well-defined factor, but they do exist and must be considered at low speeds.

All but the last item occur when d.c. motors are operated at very low speeds from standard d.c. power supplied by a variable-voltage generator. Tubes can be used to control this generator field.

Control Limitations.—The *IR* compensation voltage assumed a constant resistance in the armature circuit. Heating changes this resistance and has a very definite effect on speed regulation at very low speeds, such as require 5 to 10 volts counter e.m.f. This is true also with motor-generator set control.

At high speeds with weak field, the armature reaction on the field flux is important. An *IR* compensation voltage that will provide flat speed regulation at base speed may not be satisfactory at these high speeds, in some cases, without changes in the control.

No attempt has been made in the foregoing to show the detail connections to the control tubes, as these connections are different for the various motor sizes and according to the practice of each manufacturer. Many control applications do not require all the control tubes described.

Engineering Skill Required.—Some of the problems of tube control just stated show the importance of expert advice or an over-all guarantee from the manufacturer when selecting this control. These limitations have been overcome by careful design in the same way that other control problems have been met. Tube control developed for communications and supervisory functions will be useful in motor control, but it must be applied by engineers who understand this field of application. It will be modified for this purpose and furnishes one of the major fields for motor-control development.

PARTICULAR APPLICATIONS

It has been shown that a very small amount of low-voltage power in the grid circuit can control a large amount of power in the tube circuit; the tubes thus become amplifiers that have many applications.

They can control the field of a large generator where a motor-generator set is used to obtain a variable-voltage system of control; and can be used to give time lag, to limit the armature current, and to respond to other tube circuits.

In Industry.—Electron-tube control can be used to maintain a constant-speed relation between sections of a paper machine, the rolls of a continuous strip or plate mill, a rubber mill, or for any fabric where the process requires maintaining the tension, or loop, in the material between sections of the machine within fixed limits, as in Fig. 288.

In Communication, Remote Control, etc.—They are used in communicating, through radio, with ships, airplanes, tanks, and military stations; night fliers use them to turn on seadrome lights. The amplifying property is used to measure minute vibrations in dynamic balancing and in testing propellers for vibration. It can be used for remote control of motors to open garage doors, operate hydraulic valves, etc.

For Control through a Master Switch.—The grid circuit of an electron tube can be connected to a master switch to control the starting, stopping, reversing, and the speed of a motor. The master switch can be a pressure regulator, a float switch, a thermostat, a time clock, a speed regulator—all with split-second timing. The electron tube has made spot welding possible. It gives stepless control and accurate regulation of motor speeds.

For Control by the Light Ray.—The electron tube can transform light into electric current by replacing the heat-activated cathode with one made of photosensitive material. Light now replaces heat in causing the emission of electrons. The stronger the light, the greater the current passing through the tube. This photosensitive tube can be connected to the grid circuit of another tube, to amplify its power. The light ray that guards the entrance doors to an elevator uses this control. The light ray actuates many other types of entrance doors; it counts persons or objects passing a fixed point, spots pinholes in metal strips, protects workmen in hazardous locations, and has found many applications.

In Television and the X Ray.—Electron tubes perform other functions, such as converting electric power into light, as in the cathode-ray tube used in television reception, and indirectly, as in the X-ray tube and a fluoroscopic screen.

For High Frequency.—Electron-tube control is used to generate high-frequency alternating power, now widely used in radio transmission. High frequency is useful in the heating of metals and insulating materials in many manufacturing processes.

For Amplification.—The amplifying function may prove very useful in the more complicated systems of control, as, when it is used, so little power is required for the initiating control. The control relays controlling the grid circuit of tubes can be made very small, the burning of contacts will be eliminated, and very little heat will be developed. This type of control can be sealed up in an airtight container, to eliminate dust, corrosive gas, and moisture. The control box will be small, so that it can be readily replaced by a spare unit and taken to the shop for repairs.

CHAPTER XX

PROTECTIVE DEVICES

The National Electrical Code specifies the required branch-circuit protection for motor feeders and the minimum size of wire permitted. This overload protection is intended primarily to prevent damage to the branch feeders that would cause a fire hazard. It also affords short-circuit protection to the motor and the control, but it does not protect them from operating overloads. This latter protection is part of the controller.

In addition to overload protection, industrial controllers are commonly provided with such protective devices as low-voltage release, etc. Some of these devices are designed to protect the motor against abuse; others are for the protection of the operator or the machinery driven by the motor. The more common devices are for protection against the following conditions:

1. Overload.
2. Low voltage.
3. Phase reversal.
4. Phase failure.
5. Shunt-field failure.

OVERLOAD PROTECTION

Fuses.—The oldest form of overload protection is the fuse, consisting of a strip of metal in the main circuit that is melted, or fused, when the current exceeds a predetermined value. The earlier forms of fuse consisted of an open link. A better and more accurate fuse was obtained by enclosing the fusible link so as to give it a more definite time element and prevent the particles of molten metal from dropping on surrounding objects. Fuses are easy to obtain in the ordinary sizes, as they are carried by most supply houses. Small fuses are inexpensive where only occasional overloads are experienced. Where the motor is worked hard, with the result of repeated blowing of the fuse, the cost of fuse renewals, even for small motors, becomes excessive, and it is cheaper to use some form of overload device that does not require renewal. A knife switch should be provided for disconnecting the fuses from the line before they are renewed. Even the best designs of fuse are not very accurate, so that it is necessary to overfuse a motor somewhat to be sure of having a fuse of sufficient capacity. The inherent time element in a fuse is a distinct

advantage on a motor load, as the fuse will not respond to momentary variations in load, although it will act promptly on excessive overloads.

Fuses are now available that have a heater element in parallel with the fusible link, to increase the time of opening on normal overloads but give quick opening on a fault condition. The fusible link alone does not develop sufficient heat to melt it on normal overloads. The opening depends upon the transfer of heat to the link from the heater, which requires more time than would the direct heating of the link.

High-voltage fuses (2,200 volts and over) are made with a boric acid filler, which extinguishes the arc. These fuses have some time element inherent in their design.

Fuses used in polyphase motor circuits will cause single-phase operation if one fuse opens and, therefore, may cause a motor to burn out. Instead of fuses, three pole-circuit breakers should be used, where possible for these motors. When conditions make it necessary to use a fused switch, the heater type of fuse affords better protection.

Circuit Breakers.—The circuit breaker is a switch provided with an overload trip, which may consist of a magnet with a movable core. The attraction of the core of the magnet trips the circuit breaker and opens the circuit. Usually the current at which the circuit breaker trips is adjusted by changing the air gap between the core and its pole face. The overload trip can be provided with a dashpot for giving it a time element. This should always be done for motor loads. The overload trip of the current breaker may be a bimetal element with a heater in series with the circuit. The heater causes the bimetal to bend and trip the latch holding the breaker closed on overload. The heater element is selected for the proper tripping current. Most circuit breakers are reset or closed by hand, although magnetic reset can be provided. No new parts are required for reestablishing the circuit after the circuit breaker has opened. The continual rupturing of the circuit gradually wears away the arcing tips of the circuit breaker so that these must be renewed occasionally.

Overload Relay.—The overload relay is a small device that opens the circuit to the operating coil of a magnetic contactor or to the low-voltage coil of a circuit breaker. The relay closely resembles the overload mechanism of a circuit breaker, with the addition of the small contacts referred to above. The relays of the magnetic type (see Fig. 290) should be provided with dashpots, to give an inverse time element when they are used with motors. When the overload relay is used in connection with magnetic contactors, arrangements can be made for reestablishing the electric circuit from a push button or a master switch. When the relay trips its pilot circuit, this circuit may be maintained open by a mechanical latch on the relay or it may be opened through an electrical interlock on the magnet contactor. If a mechanical latch is used on the relay, this latch

may be released either by hand or by another small magnet. The two methods are known respectively as "hand reset" and "magnet reset." Where the circuit through the relay contacts is opened on an interlock attached to the main contactor or through another relay, the device is known as "electrically reset." The hand reset on the relay is not recommended for most applications, as it is not desirable for the operator to place his hand near the live parts on the control panel.

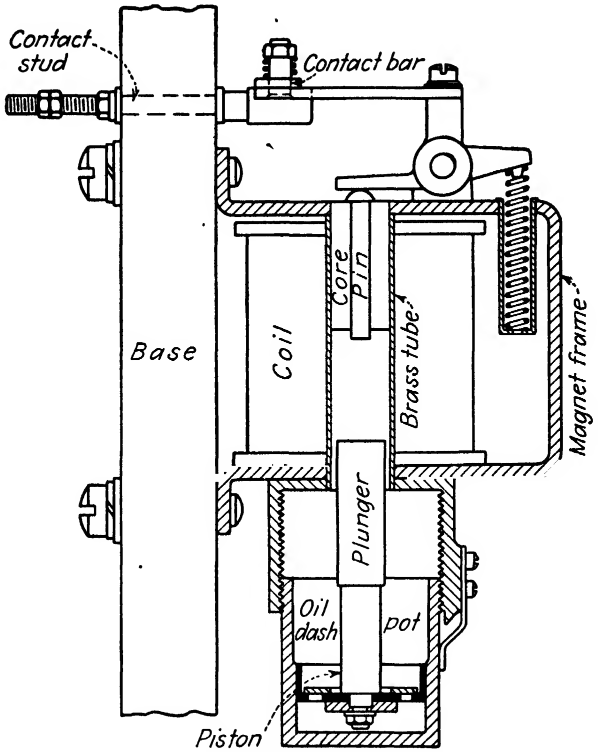


FIG. 290.—Sectional view of a dashpot overload relay—single pole. Two adjacent magnets can be used in each of two power lines arranged so that either magnet will open the contact that in turn opens the line contactor (see Fig. 291).

Time-element Overload Tripping.—The ideal overload motor protection is a device that will permit the motor to carry safe overloads for short periods, but will open the circuit when the motor begins to overheat. The device must open the circuit quickly if a fault occurs. The device should have a time-delay element that closely follows the motor temperature. This is best done by mounting the overload relay on the motor in a way that makes its tripping element follow the motor temperature. Item 14 Section I in Table 6 shows this type of relay. Additional protection is required to guard against short circuits or grounding, usually the

circuit breaker protecting the feeder. The thermal relay (Table 6, Items 5, 6, and 9 to 13) affords reasonable protection for motors operating on short-time loads, such as those of cranes, hoists, elevators, and machine tools. In many cases, the dashpot relay will be satisfactory.

The nature of the work done in most of the motor applications places a limit on the normal overload. When an accidental condition occurs, the increase in load is so much above normal, that it operates the overload device even when it is set high enough to carry the short-time peak loads. The correct selection of the motor size permits the use of an ordinary time-delay overload device.

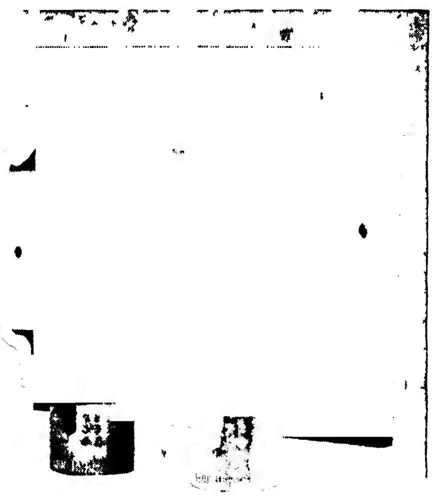


FIG. 291.—Two-magnet overload relay with dashpot time delay (see Fig. 290 for sectional view).

Thermocouples are inserted in the winding of large motors and generators and connected to switchboard instruments, to indicate the winding temperature so that the load can be properly regulated.

Overload devices with two coils or heaters usually afford reasonable protection for two- and three-phase motors and feeder circuits, but a coil in each phase is required for some conditions, as is set forth in the National Electrical Code, which should be consulted if there is any doubt as to two devices being adequate.

Figure 290 shows a commercial form of overload relay having a dashpot to give it an inverse time-element feature. Another form of relay has a copper disk rotating between the poles of permanent magnets to provide a definite time element. The dashpot type of relay is usually designed to give an inverse time element on increasing loads. Sometimes it is operated from series transformers with saturated cores, to limit the pull on

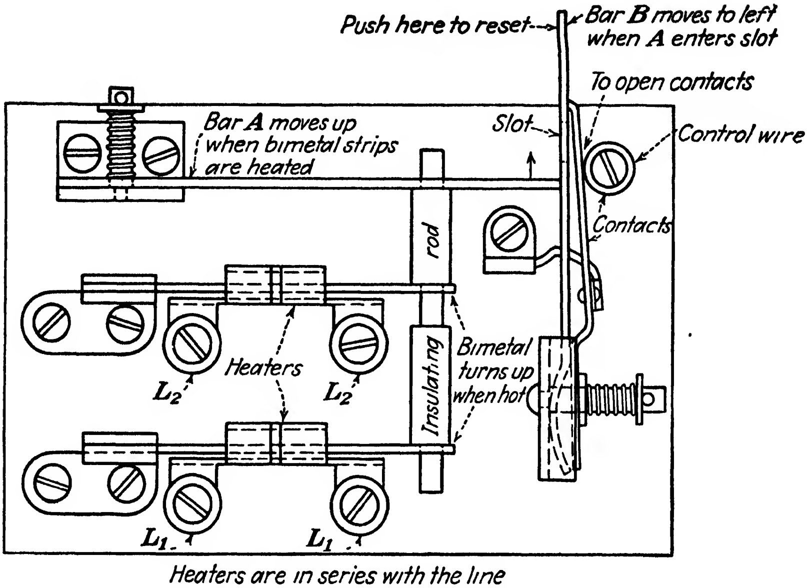


FIG. 292.—Westinghouse thermal overload relay with two overload elements of the bimetal type with heaters

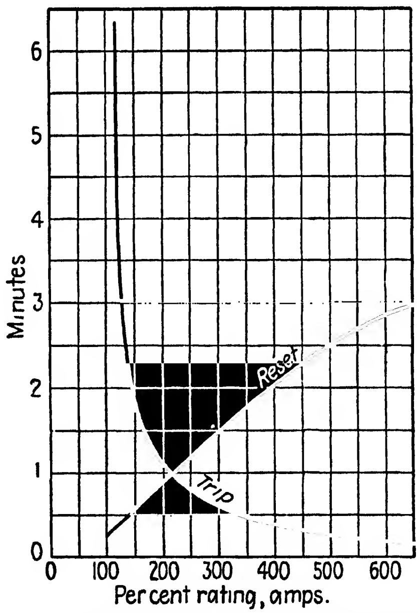
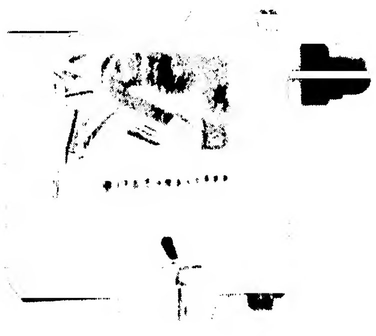
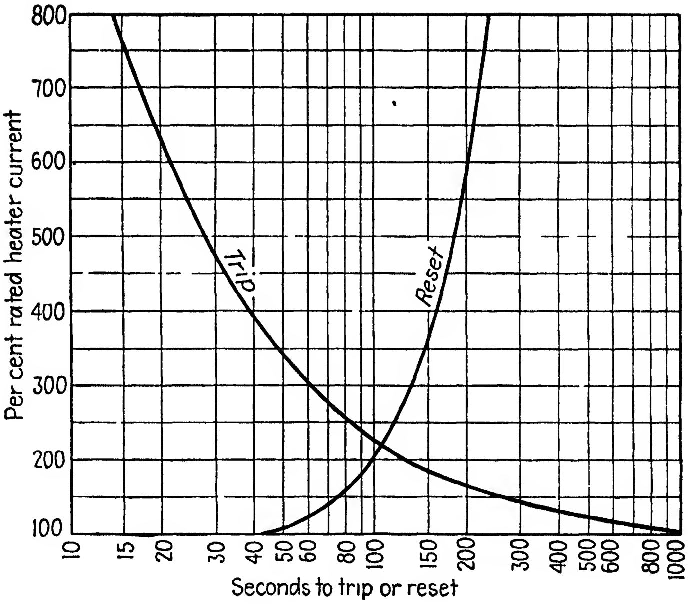


FIG. 293.—Time required to trip the relay contacts (Fig. 292) and the time required for the bimetal elements to reset





b

FIG. 294.—General Electric thermal overload relay of the bimetal type with separate heater. This isothermic overload relay gives overload protection to the motor and the machine. It can be set for either manual or automatic reset. *a*. The photograph of the relay, with the cover removed, shows heater, thermostatic strip, and control-circuit contact. The heater unit, carrying the motor current, causes the thermostatic strip to deflect upward and open the contacts with a snap action. This relay is used with 2 hp. starters. *b*. The time required to trip the relay in *a* and the time required to reset the contacts.

abnormal overloads. This latter form of relay is known as a fixed time-element relay. It is the preferable form to use in connection with a controller that is connected to a large power-supply line and is provided with a separate feeder circuit breaker for taking care of short-circuits.

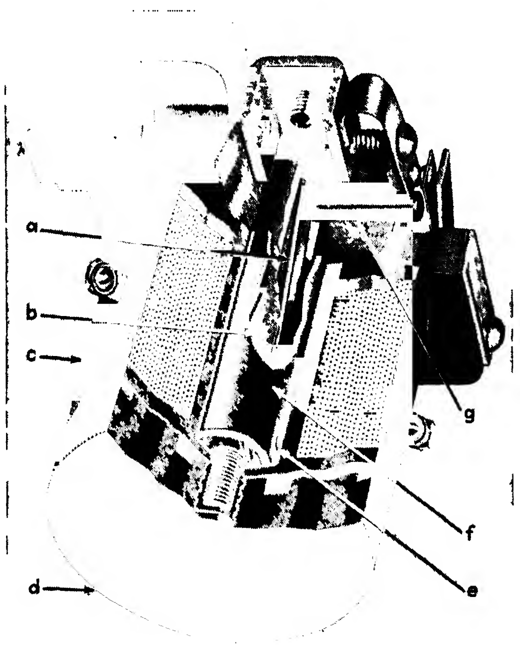


Fig 295a —General Electric oil-immersed induction type overload relay for motors only —single coil On heavy currents, that overheat the motor quickly, the relay operates quickly, on currents slightly above normal that require some time to overheat the motor, the relay action is delayed The advantage of this relay over a magnetic dashpot relay is its ability to "remember" previous intermittent overloads because of its thermal storage capacity This means that the heating element of the relay can be brought up to tripping temperature by being successively subjected to small increments of overload, which would not in themselves trip out the starter, but which would eventually create dangerous temperatures within the motor

a, Bimetallic strip that deflects when heated, opening contacts *b*, Heavy steel core provides rigid support and accurate operation under all conditions *c*, Rating determined by coil selected *d*, Coil easily removed by simply unscrewing retaining cap *e*, Bimetallic strip firmly attached to sleeve so that heat generated by current in sleeve is transmitted directly to deflecting strip *f*, Copper sleeve acts as secondary of short-circuited transformer to conduct current proportional to that in motor *g*, Plunger pin trips snap-action mechanism when overload occurs

Some operators are under the impression that it is desirable to adjust the time element of dashpot overload relays This adjustment would be desirable if a long time element were obtained Commercial forms of relays do not afford a time element that compares in length to the time required to heat up even small motors It is desirable, therefore, to

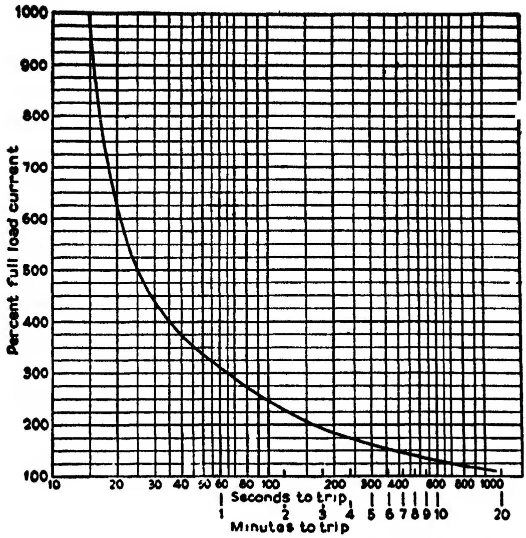
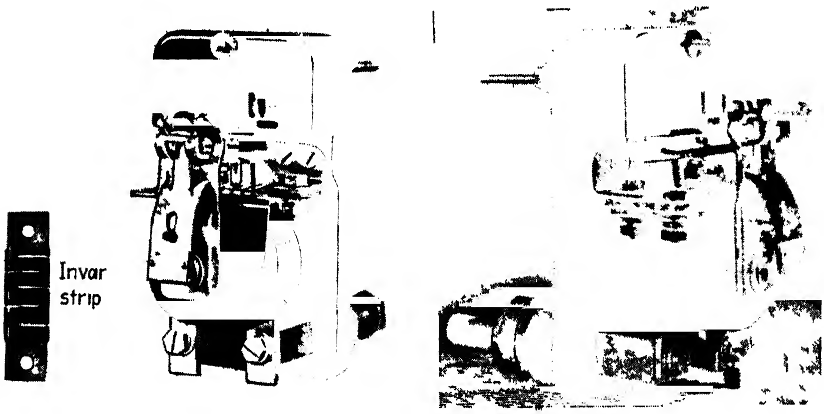


FIG 295b —The time required to trip the relay Fig 295a Note that this type of relay has a much longer time delay than the bimetal type The tripping curve shows how closely the temperature characteristic matches that of a motor



a b

FIG 296 —Westinghouse invar-type single-pole overload relay This type TI-2 overload relay has both thermal time delay for moderate sustained overloads and instantaneous trip for abnormal loads The time-delay feature makes use of invar, a metal that is magnetic at ordinary temperature but loses its magnetism at 240° C The current passes through the coil and the invar strip shown just above the coil, thence to the other lower stud Part of the magnetic flux passes through this invar strip and locks the armature in the open position until the current heats the invar strip to 240°C This gives the time-delay overload feature On very heavy overloads the magnetic pull on the armature is sufficient to break the invar lock-out pull and close the armature opening the control circuit instantly

obtain as long a time element as possible with the dashpot relay, and any adjustment provided should be set to give the maximum time element. But if too long a time element is attempted with the dashpot relay, there is a tendency for it to stick under adverse conditions. It is necessary, therefore, to adjust this time element so that the maximum time given will ensure satisfactory operation.

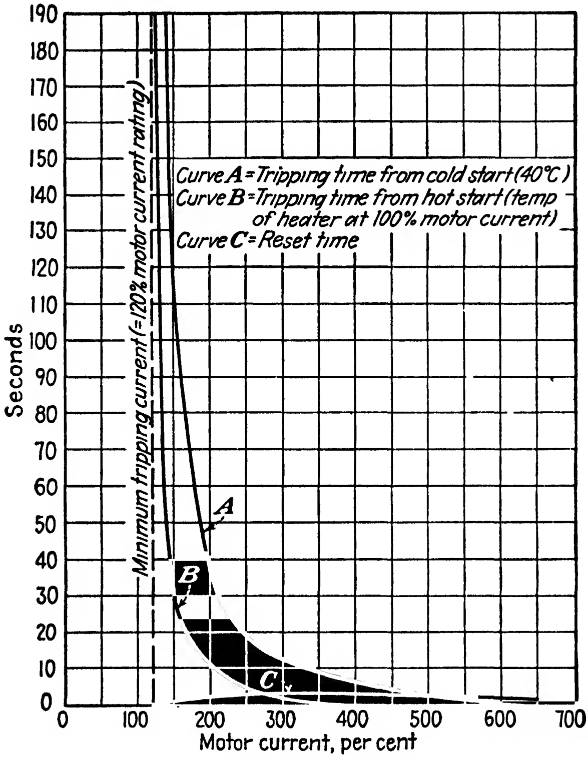


FIG 297 —The performance of relays in Fig 296.

All motor circuits should be protected by feeder circuit breakers or fuses. If the feeder circuit is connected to a very large transformer or to a power circuit having large capacity back of it, the feeder circuit breaker should be of ample capacity to take care of the power ahead of it in case of a short circuit to the feeder or the apparatus connected to this feeder. This circuit breaker must have a less time element on its trip than that obtained with the overload relay on the controller panel.

The thermal overload relay has two elements, a heater in series with the circuit to be protected and a heat-responsive element. The heater is selected to suit the ampere rating of the circuit and the time delay is the

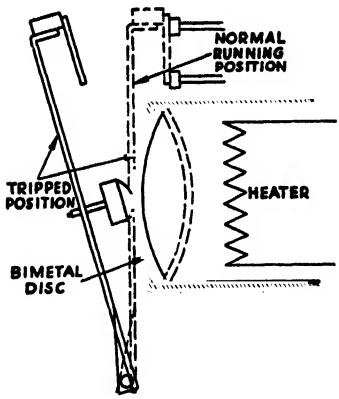
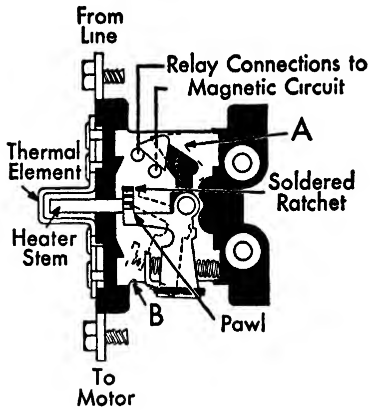
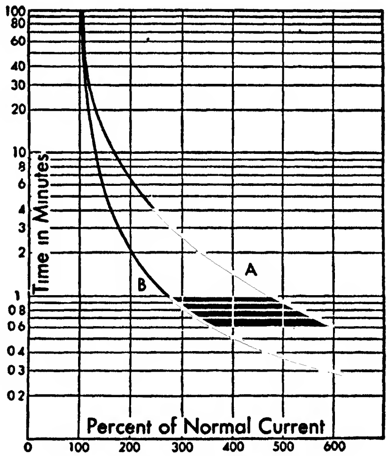


FIG 298 —Westinghouse bimetal disk overload relay Heat causes the disk to snap from the dotted position to the one shown in solid lines The contacts have quick make-and-break action.





a *b*

FIG 299 —Allen-Bradley Company thermal overload relay solder-pot type with separate heater The resisto-therm overload relay operates on the soldered-ratchet principle The heart of the relay consists of a heater stem that is almost completely surrounded by a resistance coil or resistance strip carrying the main motor current The other end of the heater stem has a ratchet wheel soldered to it This ratchet wheel engages a pawl, that holds the relay contacts closed against spring tension A sustained overload on the motor heats up the resistance unit which, in turn, heats the stem and finally melts the solder Once the solder is melted the ratchet wheel is free to turn, and the contacts are forced open by spring action This opens the coil circuit of the switch and disconnects the motor from the line The time required to open the motor circuit is very short in case of heavy overloads and much longer with light overloads Only a few seconds are required for the solder to cool and hold the ratchet wheel firmly in place, allowing the relay to be rest by pressing a Reset button The relay can be reset any number of times without affecting the accuracy or the reliability of the protection provided

a *A* shows contacts in open position Pressing Reset button transmits pressure to point *B* and thus recloses the relay *b* Current-time characteristic of the resisto-therm relay. Curve *A* is the average motor-heating curve. Curve *B* illustrates the tripping time of the resisto-therm relay

time required to transmit the heat to the tripping device. The trip operates only when the heat exceeds a fixed value. A bimetal strip is generally used as the heat-responsive element. It bends or deflects when

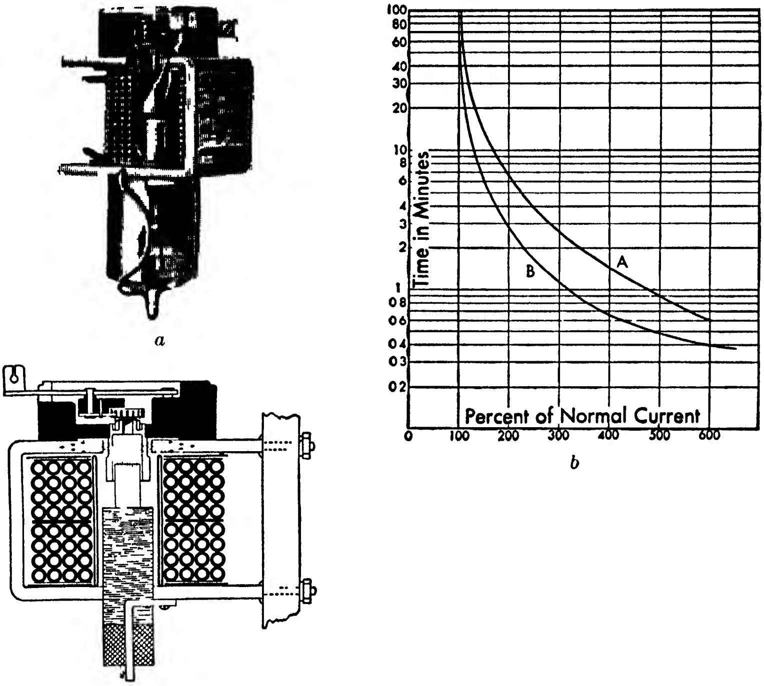


FIG. 300.—*a*. Allen-Bradley Company inducto-therm relay for a.c. motors only. The inducto-therm relay utilizes the heating effect created by a current induced in a copper heater tube.

The relay operates on the soldered-ratchet principle. Its contacts are held in a closed position by a reset lever, which engages a soldered ratchet wheel. An overload current through the magnetizing coil of the relay increases the induced current in the copper heater tube in direct proportion to the overload current, which, if the overload remains on long enough, will melt the solder, release the ratchet wheel, and trip the relay. The contacts must be reclosed manually by pushing the reset lever to the right as soon as the copper tube cools sufficiently to solidify the solder. The relay's accuracy depends only upon the melting point of the utectic solder, which is a definite value and remains constant.

The tripping value of the relay is adjustable over a wide range of current ratings by simply changing the position of the threaded iron ore within the magnetizing coil. By the lowering of the core, the magnetic flux becomes weakened and a greater overload current is required to melt the solder.

This relay can have a plunger and dashpot added to trip the retaining latch and provide inverse-time overload protection against abnormal loads such as locked rotor.

b. Time-temperature curve of relay in *a*. Curve *A* is the average motor-heating curve. Curve *B* represents the tripping time of the overload relay.

c. Diagram of *a* showing the frame, coil, threaded core, heater tube, ratchet wheel, and magnetic flux.

heated and trips the control-circuit contact open when it is heated enough. Figure 292 shows how such a relay works. The curve indicates its tripping time on various loads.

Figures 295, 296, and 300 show relays that combine time delay for normal overloads and instantaneous trip on short circuit. Figure 298 is a type of bimetal-disk overload relay.

LOW-VOLTAGE PROTECTION OR RELEASE

Devices of low-voltage protection or release are arranged for disconnecting the motor from the line on the failure of voltage. The National Electrical Manufacturers Association recognizes two forms of this protection:

Low-voltage Release.—This provides for disconnecting the motor from the line on the failure of voltage, but permits the motor to start

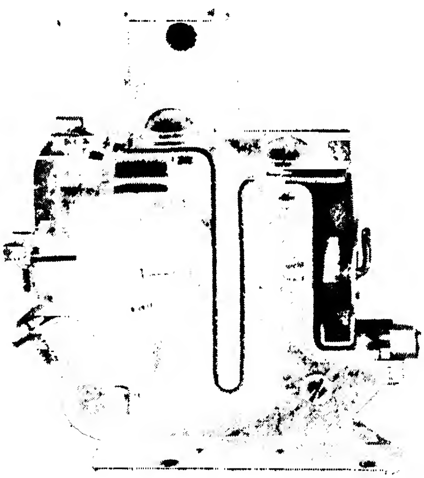


Fig. 301.—Square D Company thermal-overload relay of the bimetal type with one-half of the insulating block removed to show its operation. To the left is the control switch that is tripped by the bimetal element pressing against a pin. The dark U-shaped piece is the bimetal that is heated by the bright U-shaped "heater" projecting inside of the bimetal. The heater is selected for the correct load. The screw at the right adjusts the tripping from 85 to 115 per cent of the heater rating. The element projecting out at the top is for resetting the relay by hand when it trips or for changing it for automatic reset.

automatically when line voltage is reestablished. Such a device is the magnetic-contactor control with automatic acceleration. It is used for pumps, fans, and similar applications, which should restart automatically when the voltage is restored to the line.

Low-voltage Protection.—This device disconnects the motor from the line on the failure of voltage and prevents the motor from being started again on reestablishment of line voltage. In order to start the motor, the operator must push a button or operate a lever. This latter is a very necessary precaution where the motor is used for driving machine tools or woodworking machinery, printing presses, or in fact, any device that might cause injury to a person working on the machine.

These devices are sometimes known as "undervoltage" instead of "low voltage," both terms having the same significance. Usually they do not respond to a small drop in voltage.

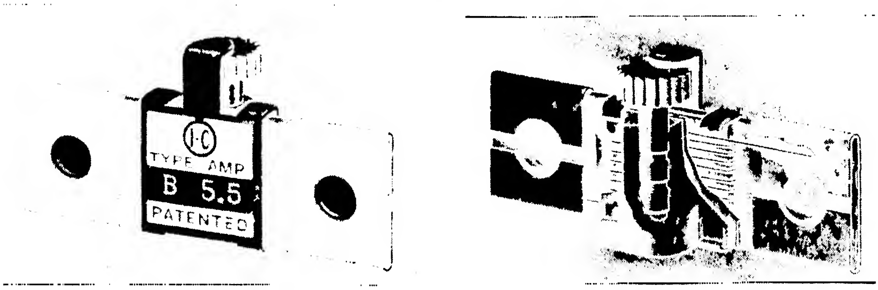


FIG 302.—The Square D Company melting alloy overload relay.

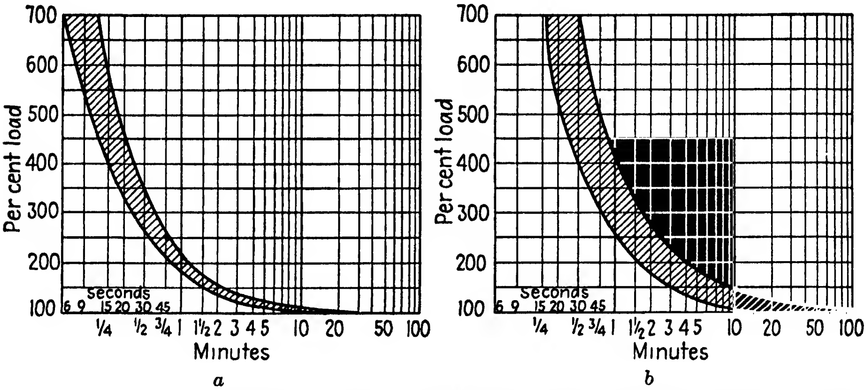


FIG 303 —Time-temperature curves of Square D Company relays a, gives the tripping characteristic of a melting alloy relay, b, gives the tripping characteristics of a bimetal relay with separate heater.

PHASE-REVERSAL PROTECTION

The device for phase-reversal protection operates to disconnect the motor from the line in case one of the phases of the polyphase circuit has been reversed. Such reversals sometimes occur when repairmen are installing service transformers or making other repairs. The effect of such a reversal is to cause the motor to operate in the opposite direction. For some applications such a reversal will not cause any damage, but where the motor drives an elevator or hoist a serious accident may result. Some public-service corporations supplying electric power to users require the installation of a reverse-phase relay device on all elevator motors to protect them from liability resulting from such an accident. There are a number of these devices now in the market. Some of them consist of a small relay having two parts, corresponding to the stationary and the movable element of a motor or wattmeter (see Fig. 304). Power supplied

to these parts causes rotation in a definite direction. The torque thus established maintains a contact in the closed position and represents normal operation. If either phase is reversed, the torque of the relay is also reversed, which opens the contact and disconnects the control and the motor from the line.

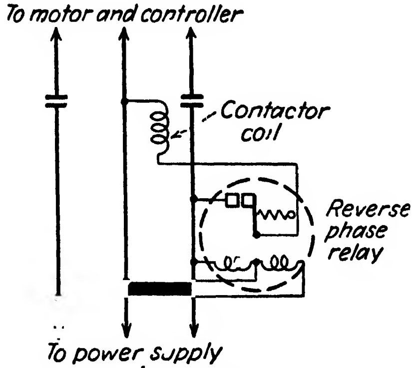


FIG. 304.

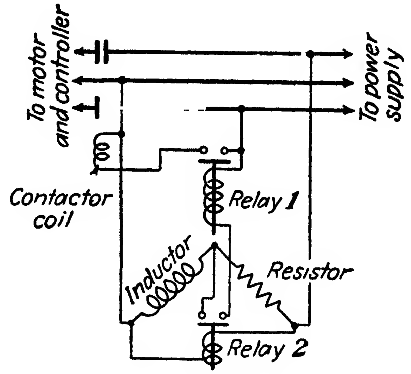


FIG. 305.

FIG. 304.—Combined phase-failure and phase-reversal relay of the wattmeter or motor type. The coil for the contactor in the motor circuit is connected through the contact in the relay. This contact is held open by a spring and is closed as a result of the torque exerted by two coils connected to two of the three phases. These coils set up a motor action that forces the contacts together against the spring pressure when the phase relation is correct. If any of the three phases is reversed, the torque on the wattmeter movement is reversed and the contact opens. If the voltage fails in either phase, the torque is reduced to zero and the spring opens the contacts.

FIG. 305.—Combined phase-failure and phase-reversal relay for a three-phase circuit. This consists of two small relays the contacts of which are closed by electromagnets. Relay 2 is connected across one phase of the circuit and remains closed as long as that phase is energized. The coil of relay 1 is connected between the three phases of the circuit, one end of the coil having an inductor in one branch and a resistor in the other branch. This combination brings the current in the two branches of the circuit so that its effect upon the coil of relay 1 is added when the phase relation is correct. On a reversal of phase relation, the currents in the two legs of the circuit through the coil of relay 1 oppose each other and the relay drops open. On failure of voltage in any one of the three phases, relay 1 is opened either directly or through the opening of relay 2. The contactor coil for the control is in circuit with the contacts of relay 1 so that the opening of this relay disconnects the motor from the line.

Another form of relay is shown in Fig. 305. This relay is made up of standard contactors. The operating coil is supplied through two circuits, as shown. One of these circuits has a resistance in series with it, the other an inductance. The resistance and the inductance cause a displacement between the two phases, so that when their effect is added the relay is maintained closed. If either phase is reversed, the phase angle is changed, causing the two circuits to oppose each other, reducing the magnetic action on the coil, and opening the relay. In the case of the two-phase arrangement, the contactor is provided with two separate coils, one in each phase.

Some devices of this character have been designed to close a circuit on reversal of phase, rather than to open it. Such devices have special

applications in connection with power circuits, but they are undesirable for industrial control, as the failure of the contacts to make a good electrical connection or the breaking of one of the wires would prevent such a device from operating. Where the contact is closed for normal operation, the breaking of a wire or the failure of the contact would disconnect the controller from the line and automatically stop the motor, which is a safer arrangement.

PHASE-FAILURE PROTECTION

Sometimes one line of a polyphase circuit may be opened accidentally. If the motor has not started, it will fail to do so and may be injured by being left connected to the line. This can easily happen in a mechanically-operated elevator control, where the failure of the motor to start might cause the operator to leave the controller in the running position. By the use of a low-voltage device across two phases of the three-phase circuit, or one relay for each phase of the two-phase circuit, the motor can be protected from such an accident. The relays are connected in such a way that the main switch will not close until both relays are closed. This arrangement is often combined with a phase-reversal relay device to give protection from both phase reversal and phase failure (see Figs. 304 and 305).

If a motor is rotating and one phase is opened, the motor will continue to operate single phase if the torque does not exceed the single-phase torque of the motor. Such operation, however, causes the whole load to be carried by one phase of the motor and may seriously overheat these windings. If the overload protection is set at a low enough value, it will protect the active phase from an excessive overload. Unfortunately, such overload devices are frequently set too high to afford proper protection. While the motor is operating, voltage is maintained across all three terminals of a three-phase motor or across both phases of a two-phase motor, owing to the active phase generating voltage in the inactive circuit. The voltage generated in the inactive circuit is very little less than the normal voltage, so that any phase-failure device depending upon a drop in voltage for operating it will not respond when connected to a rotating motor. Fortunately, many installations, such as elevators, hoists, etc., operate for only a short time without coming to rest, so that a phase-failure device will operate the first time the motor is brought to rest and prevent its restarting.

SHUNT-FIELD FAILURE

Shunt-wound d.c. motors may operate at an abnormal speed and destroy themselves by centrifugal action if the shunt field becomes dis-

connected from the line. While this kind of accident is of very rare occurrence, guarding against it in some particular cases is thought advisable. The usual method of guarding against this form of accident is to provide a relay and place its magnet winding in series with the shunt-field circuit of the motor. When this relay is energized, it closes the pilot circuit to the controller. If the shunt-field circuit should open, this relay will open the pilot circuit to the controller, which in turn disconnects the motor from the line.

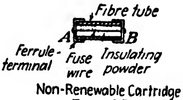
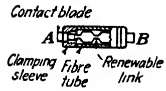
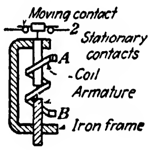
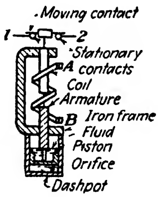
One serious objection to the use of this relay is the transformer action that takes place in the motor as a result of sudden changes of load. This action is particularly noticeable when the motor is compound wound. A rapid change in load causes a change in the field flux. This exerts a transformer action on the shunt-field windings and may be sufficient momentarily to reverse the current in these windings. This does not mean that the flux in the field circuit of the motor is reduced to zero. It simply means that the rate of change of the flux is sufficient to generate a counter voltage in the shunt-field windings large enough to cause a momentary pause in the current through these windings. This is not very hard to do, as the shunt field usually has a very large number of turns, which, multiplied by a small change in flux, will cause a considerable voltage. A reaction of this kind in the shunt-field circuit of the motor may cause the relay to drop out and disconnect the motor from the line. The connections to the controller are such that, when the relay does open the circuit, the motor will not start again automatically. It requires action on the part of the operator to reset this relay.

A number of devices have been used to delay the action of this relay to prevent an interruption of service. One method consists in adding considerable inertia to the moving parts of the relay by means of a pivoted weight or similar device. Another method is to use a heavy tube of copper around the magnet core. This copper tube acts as the short-circuited secondary of a transformer and delays any change in magnetism in the relay. Usually one or the other of these devices will prove satisfactory, although in aggravated cases additional precautions must be taken.

Engineers, as a rule, do not consider it necessary to use shunt-field protective relay except with large motors that may run light under certain conditions of load. Safety devices of any character should be avoided where they are unnecessary, as they add complication to a control equipment and require additional inspection and care to maintain it in an operative condition. It is seldom that any safety devices are used other than overload and low voltage. Wherever a safety device is used, it should be tested at frequent intervals, to ensure its proper operation in case of accident.

TABLE 7.—RELAY CLASSIFICATION[1]

I. Overload protection

Type and application	Mechanical construction	Principle of operation
1. *Fuse.* A fuse is used when overload and short-circuit protection cost must be minimized. When applying fuses, maximum ratings should approximate 150 % full-load current of d.c. and a.c. wound-rotor motors, and 250 to 300 % of full-load current of squirrel-cage motors	 Non-Renewable Cartridge Type of Fuse  Renewable Link Knife-Blade Type of Fuse	Properly applied fuse carries 110 % full-load current indefinitely. At 150 % full-load current, fuse link melts and breaks circuit in specified time in accordance with rating.
2. *Instantaneous Magnetic Relay.* Protects against high overloads. Usually calibrated to trip instantaneously at a current above motor peak starting current. Interrupting capacity of line contactor determines maximum current that can be interrupted safely.		Current through coil produces force tending to lift armature and to break contacts. Weights or springs opposing armature movement determine current value at which relay instantly trips.
3. *Time-delay Magnetic Relay.* Protects running motor against sustained currents only slightly above full-load current. Dashpot or other damping means prevents tripping on peak starting current or momentary high overloads.		Addition of dashpot to No. 2 relay prevents tripping on starting or momentary high currents. Delay period is inversely proportional to sustained overload current. Deenergization of power circuit after relay operation permits instant return of armature. Relay may be designed for closing or resetting contacts automatically, manually, or electrically. Number of turns and current capacity of coil determine specific rating.

[1] This table was prepared by R. B. Immel, design engineer, and was published in *Product Engineering*. See this publication for more details.

TABLE 7.—RELAY CLASSIFICATION.—(*Continued*)

I. Overload protection

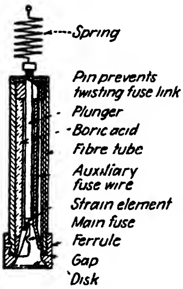
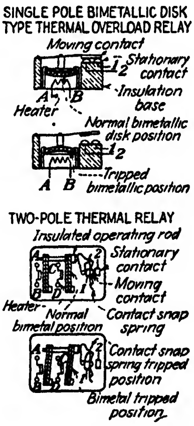
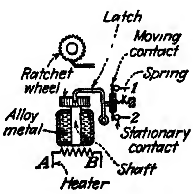
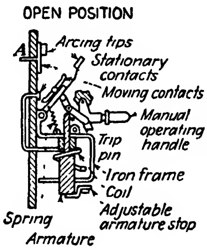
Type and application	Mechanical construction	Principle of operation
4. *Deion Boric Acid Power Fuse.* Used with low interrupting capacity switches on a.c. circuits to obtain high interrupting capacity. Installation of single circuit breaker of equal capacity and disconnecting means usually costs 20 to 50% more. Fuse is usually arranged to serve also as a means of disconnection. Links are renewable in ratings of 7.5, 15, 23, and 34.5 kv. with interrupting capacities of 0.45, 0.75, 1.0 and 1.2 million kva., respectively.		At certain current value, main fuse link burns out and releases plunger, which pulls a.c. arc through boric acid in center of tube. Auxiliary fuse wire interrupts small arc. Larger arc is extinguished by deionizing action of water vapor, which is produced by reaction between arc and boric acid, when deionization of air medium exceeds rate of ionization by the arc.
5. *Thermal Overload Relay.* Protects against sustained overload currents at 115 to 125% full-load motor current to values slightly exceeding locked rotor current. Usually ideal for running protection because thermal lag prevents tripping on starting or momentary high currents. Two separate relays or a combination relay with two or more current elements are usually employed on three-phase a.c. circuits to protect all phases and prevent the motor operating on single phase. Relay must have fuse or circuit-breaker protection against short circuits.		Heat expands one side of bimetallic disk or strip more than the other, thus causing warping or deflection, which will make or break a contact. Since deflection of flat strip is slow, a quick-acting contact mechanism is usually employed to prevent burning of contacts. Disk-type elements reverse convexity suddenly. Tripping time is inversely proportional to sustained overload current. Cooling rate of bimetal determines times for reset. Relays may have automatic or manual reset.
6. *Thermal-melting Alloy Relay.* Gives inverse time limit protection against sustained overload. Usually designed for manual reset since there is no automatic force available for resetting.		Ratchet wheel and shaft, to which torque is applied through spring latch, are restrained from rotating by low-melting alloy in bearing box. Melting of alloy at predetermined temperature produced by heating coil when sustained overload current occurs, permits contacts to open. Resetting awaits refreezing of alloy. All friction is overcome by use of a strong operating spring.

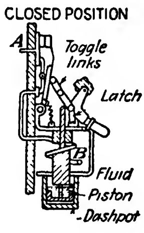
TABLE 7.—RELAY CLASSIFICATION.—(*Continued*)

I. Overload protection

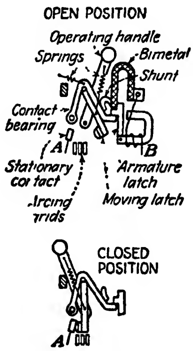
<table>
<tr><th>Type and application</th><th>Mechanical construction</th><th>Principle of operation</th></tr>
<tr><td>7. Instantaneous Magnetic-trip Circuit Breaker. Air circuit breakers have higher interrupting current capacity than most contactors. They may be considered a combination of overload relay and circuit-opening device. They are often made for a multiplicity of main circuits and may be equipped with various operating and tripping mechanisms.</td><td>



</td><td>Magnetically actuated tripping pin opens toggle-held arcing contact and main current-carrying contacts at specified overload current.</td></tr>
<tr><td>8. Time-delay Magnetic-trip Circuit Breaker. Air circuit breakers with dashpot damping are applied widely on d.c. and low-voltage a.c. circuits. Dashpot permits closer setting for tripping current because momentary or starting current peaks will not trip breaker. Oil circuit breakers, whose mechanisms and arc-quenching principles differ from those shown, are usually applied to high-voltage and high-power a.c. circuits.</td><td>



</td><td>Addition of dashpot on circuit breaker delays tripping time in inverse proportion to sustained overload current. Illustrated breaker-mechanism contacts cannot be held closed manually on high currents, as the tripping device will operate regardless of whether breaker handle is held or is free. This mechanism is called "trip free."</td></tr>
<tr><td>9. Thermal and Magnetic-trip Circuit Breaker. Combined inverse time-delay thermal and instantaneous magnetic-trip protection is obtained by a relatively simple, low-cost, and small-sized circuit breaker for low-voltage a.c. and d.c. circuits. Frequently applied to line-starter and similar apparatus for overload and short-circuit protection and disconnect-switch service. Capable of interrupting 5,000 to 10,000 amp. Single- and multiple-pole assemblies are available.</td><td>



</td><td>Contacts are closed by handle, which is connected to moving contact by a biasing spring. Thermal overload protection is provided by bimetal element, which moves trip latch when sufficiently heated. Instantaneous magnetic trip for predetermined high currents is provided by series coil and electromagnet. When latch is made ineffective by thermal or magnetic action, contact arm bearing moves to such a position that the contact is opened by biasing spring.</td></tr>
</table>

TABLE 7.—RELAY CLASSIFICATION.—(*Continued*)
I. Overload protection

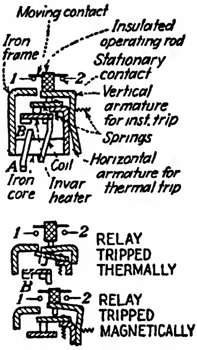
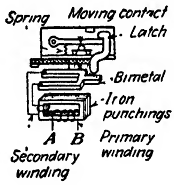
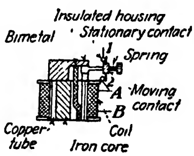
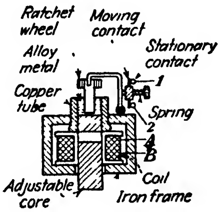
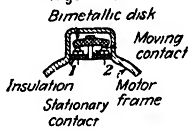
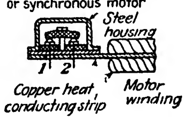
Type and application	Mechanical construction	Principle of operation
10. *Thermal and Magnetic Relay.* Used to protect d.c. motors against overload. Delay of thermal element before opening of control contacts is inversely proportional to current for low and medium overloads of 120 % or more of full-load motor current. Magnetic element trips contacts instantaneously on high overload currents of 200 % or higher.		Thermally actuated armature is normally held by spring and magnetic attraction of invar heater carrying motor current. Heater magnetism is lost at about 465°F. and armature is attracted to magnetized frame, thus opening control contacts. Separate magnetically actuated armature operates instantly on higher current. Thermal relay must be adjusted to operate at 12 to 20 % above motor current. Magnetic trip may be adjusted to operate at 200 to 600 % full-load current.
11. *Transformer-type Thermal Relay.* Current element withstands more severe overload and short-circuit currents than some other thermal relays. Can be applied only to a.c. circuits; therefore, usually built with two poles. Trips at specified value of primary ampere turns. The construction shown automatically compensates for ambient temperature.		Bimetal element is deflected upward by heat produced by secondary transformer current, which is determined by number of turns and current capacity of primary coil. Illustrated relay is compensated for ambient temperature changes by upper bimetal element, which neutralizes deflections of heated element caused by ambient temperature.
12. *Inductive Thermal Relay.* Especially suitable for oil immersion. With automatic reset it should be used only for protecting low-voltage protection circuits. For two-wire control circuits, only the manual reset or an auto-reset relay plus a reset relay should be used, the latter serving to "lock out" the control when an overload occurs.		Copper tube inside coils and around an iron core acts as a short-circuited secondary of transformer. Heat generated in tube, which is proportional to coil current and number of turns, is transmitted to bimetal element, causing it to deflect and open control contacts when damaging overloads occur.

TABLE 7.—RELAY CLASSIFICATION.—(*Continued*)

I. Overload protection

Type and application	Mechanical construction	Principle of operation
13. *Inductive Melting-alloy Relay.* Applicable only to a.c. circuits and usually has manual reset. Differs from No. 6 only in method of heating alloy metal. Relay is adjustable within certain limits for each coil.		Heat from inductively heated copper tube is transmitted to low-melting alloy around shaft of ratchet wheel. Melting of alloy at predetermined temperature produced by sustained overload current in coil permits spring to rotate ratchet wheel and open contacts. Heat generated in tube may be varied by changing position of core, thus varying the magnetic flux in the tube.
14. *Thermostatic Disk.* Protects against overheating of motors when caused by such conditions as too-frequent starting, sustained or frequent overloads, high ambient temperature, ventilation failure or abnormal voltage. Additional overload apparatus must be used if protection is required against stalling and phase failure. Bimetallic disk is usually mounted on frame of squirrel-cage motor and on winding of synchronous wound rotor or d.c. motors. It may open power circuit by means of a contactor or close an alarm circuit.	Thermostatic disk applied to squirrel cage motor  Thermostatic disk applied to windings of d c wound rotor or synchronous motor 	Principle explained for No. 5. Actual motor heat rather than that produced by heating coil actuates bimetallic disk. Resetting awaits cooling of motor frame or winding.

II. Overload relay accessories

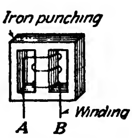
1. *Saturating Inductive Shunt.* Connected in parallel with heater of a.c. thermal overload relay to increase tripping time during starting of high inertia loads and to protect heater from high overload current. Less expensive than a current transformer.		When thermal overload relay heater carries rated current, potential drop across heater is below saturation voltage of reactor and very small current is diverted from heater. Reactor saturates at high overcurrents and a large current is shunted through it. Winding current capacity and number of turns determine rating.

TABLE 7.—RELAY CLASSIFICATION.—(*Continued*)

II. Overload relay accessories

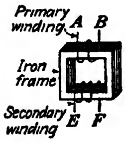
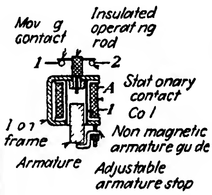
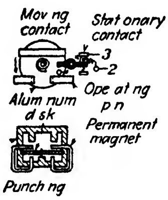
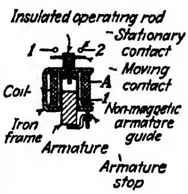
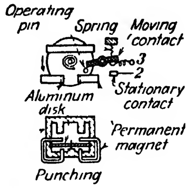
Type and application	Mechanical construction	Principle of operation
2. *Saturating Current Transformer.* Used to extend operating range of a.c. thermal overload relay heater, to increase tripping time, and to protect heater against high overload current.		When primary current is low, secondary or heater is directly proportional to ratio of primary to secondary winding turns. High primary current saturates iron core and ratio of secondary to primary current diminishes.
	III. Overvoltage	
1. *Instantaneous Relay.* Applied to circuits and equipment where an increase in voltage over normal or rated voltage may damage electrical apparatus or affect output of driven machinery.		At normal voltages magnetic attraction between armature and frame is insufficient to lift armature and open control contacts. At a voltage determined by armature stop setting, armature is lifted to break contact circuit. This voltage depends directly upon the distance between armature and frame core.
2. *Inverse Time-delay Relay.* Operates only on sustained peak voltages and will not interrupt service on momentary overvoltages. Voltage relays may be used to interlock a.c. and d.c. power supplies when both are used on the same controller. The induction type of relay is for a.c. application only.		Operates on induction principle for a.c. service only. Main potential coil is below aluminum disk. Upper two windings are energized by auxiliary coil on main pole. Interaction of magnetic fields from these coils produces torque to rotate disk and operate contacts when voltage is high. Field of permanent magnets delays disk rotation.
	IV. Undervoltage	
1. *Instantaneous Relay.* Applied to a.c. or d.c. controllers to prevent motors from operating on reduced voltage, which may affect motor speed or torque characteristics. May be adjusted to release armature, or to "drop out" at a voltage near the 'pickup" voltage, at which magnetic force closes armature.		Operation is similar to instantaneous overvoltage relay but has make instead of break control contacts. Since drop-out voltage is almost the same as pickup voltage, relay may be used to prevent starting or operating on a predetermined undervoltage.

TABLE 7.—RELAY CLASSIFICATION.—(*Continued*)

IV. Undervoltage

Type and application	Mechanical construction	Principle of operation
2. *Inverse Time-delay Induction Relay.* This relay guards against sustained undervoltages. Where circuit breakers or latched-in contactors are used, it will deenergize control circuit before voltage becomes too low to operate tripping solenoids of circuit breaker. Control circuits may be arranged so that it is impossible to start a motor unless voltage is correct.		Operation is similar to overvoltage type except for control contact. By means of slide-wire resistor, disk torque may be adjusted to close control contacts at a predetermined voltage and to release them when voltage drops. Rotation of disk through field of permanent magnets provides inverse time characteristics.

V. Polarity control

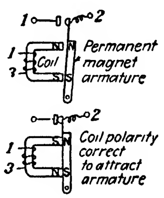
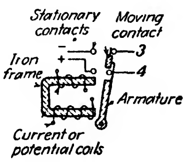
Type and application	Mechanical construction	Principle of operation
1. *Directional Relay.* In many electrochemical processes, a reversal of current may cause damage even if the current is small or of short duration. This relay operates on voltage and can prevent energization of a load circuit if its polarity is incorrect. The relay may also be used to shut down a generator if polarity is incorrect.		Direction of current flow in coil either assists or neutralizes flux from permanent magnet. Armature is held in either attracted or repelled position depending upon coil polarity.
2. *Current and Voltage Relay.* An ordinary voltage or current relay, upon which two coils may be installed, may be used for current-reversal protection. Applied to a battery charging circuit, it prevents battery discharge through generator if generator stops accidentally.		Ampere turns produced by potential coil are sufficient to operate relay. Ampere turns produced by charging current through current coil also assist in holding relay closed. If generator voltage becomes lower than battery voltage, current reverses and tends to drive generator. Reversal of current in series coil neutralizes magnetic effect of potential coil and allows relay to open.

TABLE 7.—RELAY CLASSIFICATION.—(*Continued*)

VI. Field protection

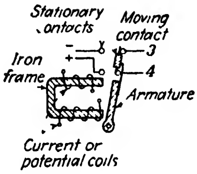
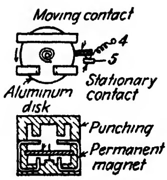
Type and application	Mechanical construction	Principle of operation
1. *Field-failure Current Relay.* Prevents starting or running of a d.c. motor with open field circuit, since coil or coils are connected in series with motor field. On adjustable-speed motors, coils must be selected so that relay will operate on minimum field current and coils will not overheat on maximum field current.		Current passing through field, which is in series with coils, operates relay so that control circuit is effective. If field current fails, relay is deenergized and control circuit opens.
2. *Differential Voltage Relay.* A field-failure current relay will not provide protection when all or part of the field is shorted out because short-circuit current may still cause the current relay to hold circuit closed. A voltage relay used as differential relay protects against short circuit and field loss resulting from winding failure.		Voltage coils are connected across identical sections of field in such manner that magnetic force from one coil neutralizes that from the other. Armature will not move while this condition exists. If this balance is destroyed by winding failure or short circuit, relay operates to stop motor.
3. *Ratio Differential Relay.* Protects against internal faults on a.c. apparatus by balancing current entering the apparatus against the current leaving it. Each phase has a relay. Leakage of current from one phase to another or to ground can be detected and the apparatus disconnected before serious damage occurs. Relays operate only on unbalance in the machine itself; not on system faults.		A field proportional to currents in sum coils reacts with field proportional to their difference. Resultant field tends to rotate disk. Quadrature flux is supplied to upper poles by transformer windings on each of lower poles. Current through sum coils tends to hold contacts closed. A current that is proportional to load current through difference coil will open contacts. Current through difference coil is the difference between input and output currents.

TABLE 7.—RELAY CLASSIFICATION.—(*Continued*)

VI. Field protection

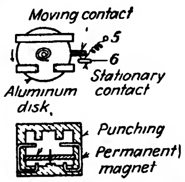
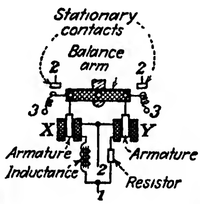
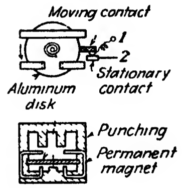
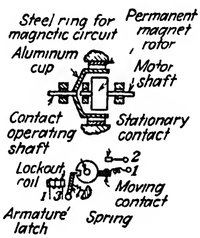
Type and application	Mechanical construction	Principle of operation
4. *Winding Temperature Relay.* Protects against excess heat in windings of a.c. motors. Before relay operates to stop a motor, (1) winding temperature must exceed calibrated value, (2) line current must be above normal, and (3) these two conditions must exist for a predetermined time. Relay will not operate on transient overload.		Operates on Wheatstone-bridge principle. Two fixed resistances in relay serve as two arms of bridge, while two copper exploring coils embedded in winding serve for other two arms. At normal operating temperature, no current flows in upper winding. If motor winding becomes overheated, bridge balance is destroyed and current flows in relay upper winding. Field thus produced by upper winding reacts with that of lower winding and produces a torque to rotate disk to stop motor.
	VII. Frequency control	
Frequency Relay. Prevents operation of induction or synchronous motor on higher or lower than normal frequency, which is proportional to motor speed.		As long as frequency for which relay is set remains constant, balance arm does not move. A change in frequency changes impedance of inductance coil and destroys magnetic balance, since any frequency change has relatively little effect on resistor circuit.
	VIII. Phase reversal or failure of bearings	
Phase-reversal and Phase-failure Relay. Prevents (1) change in direction of a.c. motor rotation and (2) operation on single phase. Reversal of phase rotation in a polyphase system reverses motor rotation. Failure of one phase would compel a motor to operate on single phase, with probable excess current and resultant overheating.		Operates on same principle as two-phase induction motor. Eddy currents induced into aluminum disk react with rotating field to produce a torque. Disk tends to rotate and holds contacts closed if line-phase rotation is correct. If a line phase opens when motor is running, spring force opens relay contact because single phase develops no torque. If phases become reversed, disk rotates to stop motor. If phase rotation is altered, a motor being started will run only an instant until relay operates.

TABLE 7.—RELAY CLASSIFICATION.—(*Continued*)

IX. Power factor

Type and application	Mechanical construction	Principle of operation
Power-factor Relay. Opens circuit and stops motor or resynchronizes synchronous motor when power factor of a.c. circuit drops below predetermined value. Principal application is to synchronous-motor controllers. Provision must be made on controller to make relay ineffective during starting period, as power factor is very low.		When voltage and current are in phase, their magnetic fields produce no torque to rotate aluminum disk. Torque from the two fields is proportional to their product times the sine of the angle between them. Relay may be calibrated to operate at 60% lagging power factor.

X. Zero speed relay

Zero Speed or Plugging Switch. Used with reversing line starter to stop a.c. motor quickly after pushing. Stop button. When rated speed of coasting motor is "plugged" down to about 40 r.p.m. by application of a voltage of such phase rotation as to produce an opposing torque, control switch opens and opposing voltage is removed. A typical device with the construction illustrated requires about $\frac{1}{20}$ hp. when driven at 1,800 r.p.m.		Motor-driven permanent magnet produces rotating field, which induces eddy currents in aluminum cup. Field and current produce torque, which rotates cup and closes its contacts. Cup is held in open contact position until speed or torque is sufficient to overcome restraining spring. Magnetic latch prevents accidental energization of control if shaft is rotated by hand. Closing and opening characteristics may be adjusted by a spring.

XI. Reverse-switch relay

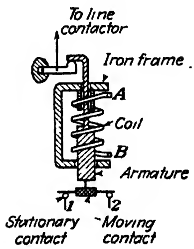
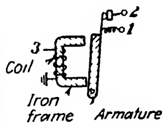
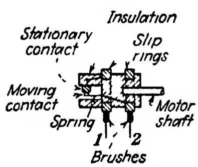
Current Relay. Prevents closing of opposite-direction contacts as long as arc exists on the opened contacts of motor-reversing controller. On high-voltage a.c. circuits, such as 2,300 volts or higher, the arcs are more difficult to extinguish when the line contactor opens. Should opposite-direction contactor be closed while arc remains on other contactor, a short circuit will occur.		Armature and moving contact mechanisms are mechanically connected to line contactor so that armature is lifted and relay contacts are opened each time contactor is operated. When contactor opens, relay armature is released and is mechanically free to fall but is held up magnetically as long as any current flows. Arc must be extinguished before relay contacts reclose.

TABLE 7.—RELAY CLASSIFICATION.—(*Continued*)

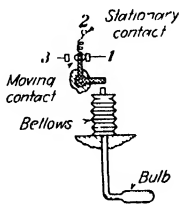
XII. Flashover protection

Type and application	Mechanical construction	Principle of operation
Voltage Relay. Disconnects motor from line if flashover occurs from commutator or slip rings to ground. Usually operates instantaneously and fast enough to prevent operation of the system-protective relays and to avoid any great damage to motor.		Flashovers usually occur between insulated circuits and frame of machine. Relay operates to deenergize motor power circuit when its voltage coil, which is connected to ground and machine frame, carries current from flashover.

XIII. Overspeed switch

Centrifugal Switch. Prevents overspeed of motor or may be used as a governor. Actuates control equipment to maintain constant speed of rotation. Often used to maintain constant speed on universal or series motors applied to busines machines.		Contacts remain closed as long as spring pressure exceeds centrifugal force when device is rotated. Speed at which contacts open may be adjusted by spring or by varying mass of moving contact. Slip rings connect rotating mechanism to circuit.

XIV. Thermal protection of bearings

Thermostatic Relay. Protects bearings, resistors, cables, transformers, etc. against overheating. Thermostatic bulb may be located in material or in contact with material to be protected Where equipment has supervision, relay usually actuates a signal to prevent unnecessary shut downs. Where supervision is not maintained, relay may be used to stop motors.		When temperature of material to be protected rises, liquid in contacting bulb volatilizes and creates pressure, which expands bellows operating toggle mechanism.

CHAPTER XXI

NATIONAL CODES, INSTALLATION AND MAINTENANCE

Two codes have been issued covering the installation of electric equipment; one has to do with fire protection and the other with safety to persons. Because control apparatus is the medium through which persons operate electric equipment and also because of its function of arc rupturing, this class of apparatus requires particular attention from the standpoints of both fire and safety. Some knowledge of these rules is necessary for a proper understanding of the controller problem.

FIRE PROTECTION

The National Board of Fire Underwriters has issued a set of rules known as the National Electrical Code. The rules of this code comprise a set of regulations that must be followed when making electric installations if such installations are to be approved by the fire insurance companies. These rules are the result of many years of experience and a large amount of research work. The National Board of Fire Underwriters maintains laboratories for research and testing. Apparatus tested by the board and meeting its requirements is listed in a publication of approved apparatus. The rules and publications can be obtained on application to the respective issuing bodies.

These rules have done great good in this country toward eliminating hazardous and flimsy construction in the design of electric apparatus and have afforded one of the incentives to maintain a high standard in electric apparatus. Any national set of rules exacts the same requirements from every manufacturer and purchaser. When properly formulated, it is fair to all and a benefit to the industry. Electrical engineers connected with manufacturing companies and customers' engineers responsible for applications have cooperated with the Underwriters in the formation of these rules, so that they represent the best combined thought in this country on the subject.

RULES FOR THE SAFETY OF PERSONS

The question of safety to persons may be considered with reference to three classes:

1. The qualified person. This includes inspectors, repairmen, and electricians charged with the installation and maintenance of electrical apparatus.
2. Operators.

3. Other persons. This classification includes the general public and all workmen or employees in an industrial establishment who are not directly charged with either the maintenance or the operation of any particular electric equipment.

The question naturally arises as to who is a qualified person. At present, any manufacturer or owner may employ and authorize a person or persons to install, inspect, and maintain electric equipment. It is probable that, should an accident occur, the employer would be called upon to show that he had exercised care in the selection of such employees. In the future, legislation may require such persons to pass an examination and be licensed for this work.

Injury from electric apparatus may result in a number of ways, the more common being as follows:

1. Touching live parts.
2. Arc or flash.
3. Touching hot parts.
4. Explosion of fuses.
5. Gas or dust explosions.
6. Injury from moving parts of a controller.
7. Phase reversal.
8. Unexpected starting.
9. Overspeed.
10. Lack of emergency stop.
11. Overtravel.
12. Failure of power.
13. Overload.

Most of these hazards are avoided by the proper design and installations of the electric equipment.

The two hazards that most often result in accident are touching live parts and arc or flash. The arc or flash may injure a person by direct burning or by exposing his eyes to the rays of the arc. They are familiar to most electrical engineers.

There are three general methods of guarding against the first six hazards mentioned. These are

1. Enclosure.
2. Isolation.
3. Guards.

The use of enclosures for all electric apparatus is rapidly extending. In industrial plants, the controller and switching mechanism will often be found protected by cabinets or other suitable means. I believe that we will soon use covers over the commutators and brushes of motors. All electrical connections should be made by means of conduit. These enclosures, of course, add something to the first cost of the equipment but, when they are properly designed, the cost is not out of proportion to the

results obtained. Even where state or local laws do not require this protection, we must never forget that our industrial workers are human beings of varying ages, and that many of them have the instinctive curiosity of youth and are inclined to investigate any apparatus that they do not understand.

Apparatus may be isolated so that it is accessible to qualified persons only, by one of the three following methods.

1. Installed in a separate room with a locked door.
2. Installed on a balcony, gallery, or platform so elevated and arranged as to exclude other persons.
3. Elevated at least 8 ft. above the floor line or working platform.

The first method is used for large motors, generators, and switchboards where the expense of a separate room accessible only to authorized persons is justified. The other two methods are used for small motors and controllers installed about a manufacturing plant.

Electric apparatus may be guarded by partitions, screens, fences, or rails, so arranged that only qualified persons may have access to the space within reach of this apparatus. This is a convenient method of protecting large switchboards or control panels, as well as large motors and generators, where a separate room cannot readily be provided.

The National Electrical Safety Code gives a very full and complete discussion of the various forms of hazard and the protection against such hazard. This code does not go into sufficient detail for working purposes. It is, therefore, necessary to supplement this work with more detailed description and rules.

Grounding.—In most cases the enclosure of the controllers or the frame of the machine should be grounded. This requirement is obvious to those versed in the art. The exception to grounding is where the apparatus is accessible only to qualified persons and where insulating mats, platforms, or floors are provided surrounding the apparatus. In such cases no grounded parts should be within reach of the person working on the electric equipment.

Disconnecting Means.—It is recognized that all electric equipment requires inspection, adjustment, and some repairs, such as renewals of brushes, contacts, etc. In order that it may be safe for a qualified person to perform this work, provision should be made for entirely disconnecting the apparatus from the source of electrical supply.

Where this disconnecting means is not within sight of the person working on the apparatus, means should be provided for locking it in the open position. This is usually done by a padlock. This requirement is also necessary where the apparatus driven by the motor is undergoing repairs or adjustments. Accidents have resulted from the unexpected starting of a conveyor or other machinery when a workman was repairing it.

The unexpected starting of a motor frequently results in accident. This can usually be guarded against by the proper design of control equipment. Low-voltage protection can be provided to prevent unexpected restarting after a failure of power. The controller handle either may be removable or may be provided with a latch or lock in the Off position. The controller handle may catch in the clothes of a person working around this apparatus or it may become entangled in other apparatus that is being drawn by on trucks, etc., and the motor be started unexpectedly. A latch will prevent this.

All control apparatus should be so arranged that the circuit to the motor will be opened and remain open in case a pilot wire or a contact should fail. The only safe arrangement of a protective circuit is to permit operation only while the circuit is intact. The breaking of a wire or failure of power from some other cause should stop the motors.

Working Space.—In installing electrical apparatus, suitable working space should be provided and maintained about the equipment. Where a motor or a controller is mounted above the floor level, a suitable platform or other means of access should be provided. Although this is only a common-sense requirement, it is often overlooked

Location of Controller.—It is desirable to have the controller located so that the motor and driven machinery will be in sight of the operator during the starting period. Where an arrangement of this kind is possible, the operator can observe the apparatus during the starting period and, if an accident should occur, he can stop the motor promptly. Where the operator cannot be located so as to observe all the machinery during starting, additional precautions should be taken to protect persons who may be in or about the machinery at that time. For instance, Stop buttons may be located at various convenient points that will enable some other person to stop the machinery promptly in case of accident. Another precaution would be to arrange the controller handle or the disconnecting means so that it can be locked in the open position by any person who might have occasion to work on the machinery and would be in danger if it were accidentally started.

Resistors.—Resistors are used for the purpose of starting and regulating the speed of motors. Their function is to absorb electric energy and dissipate it as heat. In order that they may function properly, they must be provided with a reasonable amount of ventilation. This means that large units should not be located in a corner of the room remote from windows, or in any other restricted position. This is particularly true of resistors used for regulating the speed of motors. Unless the motor is very large or is started very frequently, the energy stored in the resistor during the starting period is small and the ventilation in the case of resistors used for starting only is not so important.

Resistors should not be mounted close to combustible material. When the resistor is mounted on the wall, an air space should be left between it and the wall. In general, it is safe to consider the resistor a mild form of stove or other heating apparatus and to take the same precautions in its installation that would ordinarily be taken in locating a stove or small heater.

FIELD MAINTENANCE

A systematic program for inspection and maintenance should be established and closely supervised. An adequate stock of renewal parts should be kept. The manufacturer will furnish a recommended list of such parts.

Careful attention should be given to the following instructions:

Clean the control of loose dirt with a low-pressure air jet or a hand bellows. Use a soft cloth for wiping the contacts and insulation. Do not use waste, as it sometimes contains metal particles. Renew dashpot oil frequently if it gets dirty and gummy.

Inspect contact surfaces and adjust them so that contact is made throughout their entire width. Clean sliding contacts with fine sandpaper and remove the burrs with a file. Rolling contacts usually do better if not dressed down, as they burn to a good, though irregular, contact surface. Renew both contacts of a pair, when necessary, as a new one will not make good contact with an old one. Contacts that are seldom opened build up an oxide film on the contact surface and should be cleaned at frequent intervals with fine sandpaper. Use a small spring balance (see Fig. 32) to measure the closed-contact pressure and keep it within the limits specified by the manufacturer. Renew contacts before they wear down to a point where they do not properly function.

Sliding contacts, such as in drum controllers, should be greased with a thin film of Vaseline. Wipe off all surplus Vaseline with a soft cloth. Do not use any lubricant on the sliding surfaces or bearings of controllers exposed to abrasive dust, as the lubricant holds the grit on the surface and increases the cutting action. Clean all surfaces before lubricating. Adjust drum controller fingers so that they drop $\frac{1}{16}$ to $\frac{1}{8}$ in. below the drum surface.

Clean the arc-box surfaces adjacent to the contacts, as the arcing may form a conducting crust on these surfaces and interfere with extinguishing the arc.

Examine shunts for signs of breaking and renew them when necessary. See that the shunts are not distorted in any way.

Check a.c. magnets to see if the armature seats properly; an increase in the closed air gap overloads the operating coil and may destroy it.

Clean and adjust all secondary contacts. Check all connections to be sure that they are tight.

Check all safety features for proper operation. Before leaving, inspect the controller operation under load. An experienced man will note any parts that are not working properly.

Overhauling.—From time to time, it is necessary to dismantle a controller for major overhauling. The insulation should be thoroughly cleaned and varnished. Remove parts clamped to the insulation and repair any damage. Renew asbestos linings of controller covers when they are exposed to arcing.

Make sure that any paint or varnish used has suitable insulating properties.

Renew worn bearing pins and bushings. Keep the diameter the same, so that standard pins will fit.

Clean all clamped surfaces that carry current and give them a thin coating of solder to prevent oxidation.

Examine all soldered joints and connections for corrosion from acid flux. Nonacid flux should be used.

Paint all iron surfaces with good black enamel.

The best results are obtained by using the renewal parts furnished by the manufacturer.

CHAPTER XXII

FUTURE CONTROL DEVELOPMENTS

Prophecy is difficult but fascinating and sometimes useful if it is based upon experience. New developments are continually being made, some of them representing a definite departure from existing practice. All these changes must have careful consideration before they are placed on the market, as existing apparatus represents a large investment in engineering designs, tools, stock parts, printed matter, and the education of users.

The Second World War has forced the development of many new things that will be made available to the public after the war. One of these is the electron tube, which is already in commercial use for motor control. It provides one method for converting from a.c. to d.c. power, with voltage control for adjustable speed of d.c. motors. Close speed regulation can be obtained with both current and torque control and other features can be added. We should expect important development in tube control for motors.

Electron tubes can be used to convert from a fixed frequency to other frequencies by converting from a.c. to d.c. power and then from d.c. to a.c. power at the desired frequencies. This is a double conversion, but the simplicity of the squirrel-cage induction motor and the absence of exposed contacts make it very desirable for some applications and, if it can be supplied with adjustable frequency, there may be a real demand for such a control. Very little attention has been given to the hydraulic speed changer (similar to the Waterbury gear) for general-purpose applications. This device consists of a series of small adjustable-stroke pumps driven by a constant-speed motor (probably a synchronous motor). The load is driven by a similar device having a constant stroke. Its speed depends upon the volume of oil delivered by the pumps. When the pumps are reversed, the receiving device also reverses.

This speed changer provides means for operating and reversing a load and changing its speed, all from a constant-speed synchronous motor, simply by mechanically changing the stroke and direction of the pump. A small pilot motor will effect this change and can have electron-tube control. The electrical problem is simple, the real work is in producing the "hydraulic gear" at a cost that will give it this market. The hydraulic drive for automobiles may point to another device for this purpose.

It is probable that apparatus and systems used in telephone practice will prove useful in the supervisory part of motor control. This is particularly true where electron tubes are used as part of the control. Radio signals and response have had some limited use in control and may be useful on a coding basis for initiating the control of motors where the installation and maintenance of wire control is difficult or where a portable master switch is used. Communication control is not very far removed from motor control; it requires only a working knowledge of another type of equipment.

More study will be given to power-factor correction and means for reducing the short-time peak loads. This will relate more to control systems than to control units. Existing designs will continue to be simplified, to be made more reliable and more compact, and to be produced at a reduced first cost. Protection to persons is of increasing importance; this will influence control design to improve its protection against arcing and the exposure of live parts.

Improvements in details always continue, with an occasional long step forward accomplished by some departure from existing methods or equipment. Every generation has its pioneers, often in the smaller companies that require novelty to widen their distribution. Motor designs are well stabilized, but the control field continues to offer many possibilities for new methods, greater convenience, better performance, and increased protection to persons and to property.

REFERENCES

For supplementary reading, the following references are suggested:

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Harwood, Paisley B.: "Control of Electric Motors," John Wiley & Sons, Inc., New York (1936). Gives certain interesting details not included in the present book, and treats the subject from a slightly different point of view.

National Electrical Manufacturers Association (1938). A standard publication on industrial control standards which will be very useful to anyone interested in the subject. Some extracts from it are included in this volume.

Shoults D. R., and C. J. Rife, "Electric Motors in Industry," Chaps. IX–XI, John Wiley & Sons, Inc., New York.

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